UNION OF ENGINEERS AND TEXTILE TECHNICIANS OF SERBIA

9th INTERNATIONAL SCIENTIFIC CONFERENCE

CONTEMPORARY TRENDS AND INNOVATIONS IN THE TEXTILE INDUSTRY

PROCEEDINGS

EDITOR:
Prof. dr SNEŽANA UROŠEVIĆ

Belgrade, 17-18th September 2026.

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AND

UNION OF ENGINEERS AND TECHNICIANS OF SERBIA
FACULTY OF TECHNOLOGY AND METALLURGY IN BELGRADE
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PREFACE

The 9 th International conference "Contemporary Trends and Innovations in the Textile Industry" CT&ITI 2026, is co-organized by:

- Union of Engineers and Textile Technicians of Serbia,
- Union of Engineers and Technicians of Serbia,
- Faculty of Technology and Metallurgy in Belgrade, University of Belgrade, Sebia,
- Faculty of Technology, Shtip, Goce Delchev University, North of Macedonia,
- Faculty of Mechaical Engineering, Polytechnic University of Tirana, Albania,
- Society for Robotics of Bosnia and Herzegovina and
- Balkan Society of Textile Engineering-BASTE of Greece.

The Ministry of Science, Technological Development and Innovation of the Republic of Serbia recognized the importance of this Conference, and thus, supported it.

The aim of this Conference is to consider current technical, technological, economic, ecological, R&D, legal and other issues related to the textile industry, then the application of contemporary achievements and the introduction of technical and technological innovations in the production process of fiber, textile, clothing and technical textile by applying scientific solutions in order to improve the business and increase the competitive advantages of the textile industry on the domestic and global market.

Leading scientists and experts from the Balkans and other countries, working at faculties, textile colleges and institutes, but also individuals who professionally deal with the issues at hand are taking part in this Conference.

The program will include the latest achievements in the fields of advanced textile materials, sustainable production, environmental protection, design of textiles, clothing, leather and footwear, application of artificial intelligence and smart technologies in the textile industry, as well as textile cultural heritage, which is included among the official topics for the first time. The conference has an interdisciplinary character and connects education, innovation, sustainability and the needs of the economy into a single whole. The Conference program involves papers dedicated to the scientific and practical aspects of the following topics: Textile Technology, Design, Management and Marketing, Ecology and Sustainable Development, Leather and Footwear, and Textile Heritage.

The Conference program includes 62 papers, and a total of 152 participants from 10 countries: Bosnia and Herzegovina, Bulgaria, Greece, Germany, Hungary, India, North of Macedonia, Slovenia, Serbia and Turkey.

Therefore, this Conference is an opportunity for establishing scientific, educational and economic cooperation of our country with other countries. Certain number of papers by domestic authors present the project results dealing with fundamental research and technological development, financed by the Ministry of Ministry of Science, Technological Development and Innovation of the Republic of Serbia.

I would like to thank all those who have made it possible to organize the conference Contemporary Trends and Innovations in the Textile Industry and make it a success. First, I would like to thank the Scientific and Organizing Committee for working hard, spending countless hours and finding the best solutions for numerous organizational aspects of our Conference. I also thank all the other institutions that supported the Conference in various ways, because without their support, the Conference could not have been organized. Last but not least, I would like to thank plenary lecturers, all authors and co-authors and guests for their participation in the Conference.

On behalf of the Organizing Committee
Prof. dr Snežana Urošević, president

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PLENARY LECTURES

LEARNING TRADITIONAL TEXTILE TECHNIQUES: WET FELTING AS A PEDAGOGICAL APPROACH IN CONTEMPORARY TEXTILE DESIGN

Professional paper
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ABSTRACT: *The growing demand for sustainable practices in the textile industry has highlighted the importance of integrating traditional craft knowledge into contemporary design education. Historical textile techniques offer valuable insights into material properties, low-impact production processes, and culturally embedded knowledge systems that can contribute to more responsible design approaches. Among these techniques, wet felting represents one of the oldest textile manufacturing processes based on the natural properties of wool fibers and their ability to interlock through moisture, heat, and mechanical action. This paper examines the pedagogical potential of wet felting within contemporary textile design education. The study focuses on an educational process that combines experiential learning with the transmission of traditional craft knowledge through collaboration with artisans. Students explore the material intelligence of wool through hands-on experimentation with wet felting techniques. The learning process further introduces nuno felting, a more recent textile technique developed approximately three decades ago, which integrates wool fibers with lightweight fabrics and enables contemporary design interpretations. The research adopts a practice-based pedagogical approach integrating theoretical reflection, material experimentation and design development. The results indicate that learning traditional techniques enhances students' understanding of material behaviour, fosters sustainable thinking and encourages innovative textile design exploration.*

Keywords: *wet felting; textile education; sustainable textile design; craft knowledge; textile heritage.*

UČENJE TRADICIONALNIH TEKSTILNIH TEHNIKA: MOKRO PUSTOVANJE KAO PEDAGOŠKI PRISTUP U SAVREMENOM DIZAJNU TEKSTILA

APSTRAKT: *Rastuća potreba za održivim praksama u tekstilnoj industriji naglasila je značaj integrisanja tradicionalnih zanatskih znanja u savremeno obrazovanje u oblasti dizajna. Istorijske tekstilne tehnike pružaju dragocene uvide u svojstva materijala,*

proizvodne postupke sa manjim uticajem na životnu sredinu i kulturno ukorenjene sisteme znanja koji mogu doprineti odgovornijim dizajnerskim pristupima. Među tim tehnikama, mokro pustovanje predstavlja jedan od najstarijih postupaka proizvodnje tekstila, zasnovan na prirodnim svojstvima vunenih vlakana i njihovoj sposobnosti da se povezuju pod dejstvom vlage, toplote i mehaničkog delovanja. Rad razmatra pedagoški potencijal mokrog pustovanja u savremenom obrazovanju za tekstilni dizajn. Istraživanje se fokusira na obrazovni proces koji povezuje iskustveno učenje sa prenošenjem tradicionalnog zanatskog znanja kroz saradnju sa zanatlijama. Studenti istražuju materijalnu inteligenciju vune kroz praktično eksperimentisanje tehnikama mokrog pustovanja. Proces učenja obuhvata i nuno pustovanje, noviju tekstilnu tehniku razvijenu pre približno tri decenije, koja povezuje vunena vlakna sa laganim tkaninama i omogućava savremene dizajnerske interpretacije. Istraživanje se zasniva na praksi orijentisanom pedagoškom pristupu koji objedinjuje teorijsku refleksiju, materijalno eksperimentisanje i razvoj dizajna. Rezultati ukazuju da učenje tradicionalnih tehnika unapređuje razumevanje ponašanja materijala kod studenata, podstiče održivo promišljanje i ohrabruje inovativno istraživanje tekstilnog dizajna.

Ključne reči: *mokro pustovanje (mokro filcanje); tekstilno obrazovanje; održivi tekstilni dizajn; zanatsko znanje; tekstilno nasleđe.*

1. INTRODUCTION

Textile design education is increasingly expected to connect material knowledge, sustainability, heritage, and innovation. These concerns remain abstract when they are separated from direct engagement with material processes. Wet felting provides a focused learning situation: loose wool is transformed into a coherent nonwoven structure through water, soap, heat, pressure, friction, and time. At each stage, students can observe how an initial fiber arrangement becomes a surface and how process decisions influence density, shrinkage, handle, and form [7-10].

This professional paper examines wet felting as a pedagogical method across two linked learning settings. In the first stage, students attended wet-felting and nuno-felting workshops led by artisan Anja Musek at her AMUSE art studio in Škofja Loka. Through fiber preparation, directional layout, wetting, rubbing, rolling, fulling, and the integration of wool with lightweight fabrics, they acquired an embodied understanding of both techniques. In the second stage, within the first-year Textile Techniques course in the Fashion and Textiles program at the Faculty of Design, students applied this technical knowledge in a sustained material and structural investigation. Responding to AIR / ZRAK, the publicly announced theme of BIEN 2025, each student developed an individual conceptual spatial textile work. Rather than presenting wet felting as a hobby practice or an automatic sustainability claim, the paper considers how a traditional technique can support material understanding, reflective making, and contemporary textile design development.

The paper is a practice-based, reflective account rather than a controlled study of learning outcomes. Its evidence consists of workshop photographs, sample sets, process notes, the lecturer's reflective observations, and selected final works. Because the author was also the lecturer responsible for the second stage, the account is explicitly reflexive. In the abstract, the term results is used in a descriptive, case-based sense: the documented material experiments and design outcomes make visible the process variables and design consequences encountered by students; they do not quantify or isolate causal learning effects.

2. WOOL, FELT AND TEXTILE CULTURE

Sheep were among the early domesticated livestock species of Neolithic West Eurasia. Recent archaeogenomic research places key domestication processes in Southwest Asia and demonstrates the subsequent movement, admixture, and diversification of sheep populations across Eurasia [1]. Sheep domestication, however, should not be equated with intensive wool production. Archaeological research indicates that wool and wool textile production became increasingly important in parts of Europe during the Bronze Age, as selective breeding, herding practices, and textile technologies developed together [2].

Felt occupies a distinctive position within textile history because it is made without spinning yarn or weaving cloth. Prepared wool fibers are arranged in layers and consolidated into a nonwoven textile through wetting, agitation, pressure, and fulling. Historical and ethnographic accounts document felt in pastoral and nomadic settings as insulation, protective covering, padding, floor covering, horse equipment, clothing, and shelter material [3-5]. Its importance lies not in technological simplicity, but in the close relation among material properties, climate, labor, mobility, and use.

For contemporary design education, this history is valuable when it is approached as material intelligence rather than as a source of decorative motifs. Traditional felt can be studied for the way it integrates fiber, body, environment, maintenance, and practical purpose. The pedagogical task is therefore to translate this structural logic into present design questions rather than to reproduce historical forms uncritically

3. WOOL AS MATERIAL BASIS FOR WET FELTING

Figure 1. Electron micrograph of a clean Merino wool fiber showing overlapping cuticle scales. The scale structure contributes to the directional friction central to wet felting. Source: CSIRO ScienceImage 2487 (2000), CC BY 3.0; cropped [6].

As shown in Figure 1, the surface of a wool fiber comprises overlapping cuticle scales, a structural feature central to the directional-friction effect involved in wet felting. Wool is an animal protein fiber composed primarily of keratin. Its structure includes an external cuticle of overlapping scales and an internal cortex that contributes to strength, elasticity, crimp, and resilience. Fiber fineness, staple length, crimp, cleanliness, and preparation all influence the behavior of a developing felt [7-10]. These are not background facts; they are variables that students encounter in every sample.

Wool's directional-friction effect is central to felting. When wetted and subjected to rubbing, rolling, compression, and progressive fulling, fibers migrate, bend, entangle, and lock. The resulting material is neither glued nor woven; it is a consolidated textile formed through entanglement, shrinkage, and compaction [7,9,10]. Shrink-resistant or superwash wool is generally unsuitable for conventional wet felting because its surface has been modified to reduce scale interaction. This contrast is pedagogically useful because it shows that felting is not a generic property of all wool products, but depends on fiber structure and preparation.

Material explanations become meaningful when they are tested through the hands. Students can register the transition from loose fiber to a provisional web, from a fragile web to a surface that holds, and from that surface to compact felt. They can also compare the consequences of fiber quantity, directional layout, water and soap, pressure, duration, and finishing. The workshops therefore treated sampling, comparison, and documentation as integral parts of learning rather than as secondary records of a finished artifact.

4. LEARNING THROUGH MAKING: PEDAGOGICAL FRAMEWORK

Wet felting is a direct material experience, but its educational value lies in a structured cycle of action, observation, interpretation, and adjustment. Kolb's model of experiential learning and Schön's account of reflective practice are useful because both describe knowledge as developing through the transformation of experience and through judgment in action [14,15]. In a wet-felting session, the cycle is concrete: a student arranges fibers, observes instability or uneven shrinkage, considers a possible cause, changes the next intervention, and encounters the consequence in the developing textile.

This sequence gives educational value to failure only when failure is made legible. A surface that separates, develops holes, shrinks unevenly, or loses its intended transparency is not a wasted sample when students can identify what happened and revise the process. Kapur's concept of productive failure is relevant here because it distinguishes unstructured frustration from exploration that is later consolidated through guidance and reflection [16]. In this context, the sample becomes both outcome and evidence: a material record of choices that can be compared, annotated, and used to guide the next attempt.

In this teaching sequence, collaboration with an artisan provided access to strongly embodied knowledge. An experienced felt maker can calibrate pressure, rhythm, fiber placement, surface resistance, and the timing of fulling in ways that cannot be wholly reduced to a checklist. This corresponds to the tacit knowledge described by Polanyi and to the relation between hand, material, and judgment discussed by Sennett [17,18].

Research on the transmission of master-craft knowledge and on material experimentation in studio education likewise supports the value of observation, correction, and repeated practice [19,22].

5. NUNO FELTING AND CONTEMPORARY DESIGN INTERPRETATION

After basic wet-felting processes have been established, nuno felting introduces a more complex relation between wool and cloth. Practitioner accounts associate the term and technique with Polly Stirling and Sachiko Kotaka, who described developing Nuno Felt in 1994 by working a small amount of wool through a fine base weave [20]. Nuno felting combines wool fibers with lightweight or open-weave fabrics, allowing the fibers to migrate through the cloth and create a hybrid textile in which fiber quantity, fabric openness, layout, shrinkage, and finishing jointly determine the result.

Pedagogically, nuno felting makes relation rather than decoration the central problem. Wool does not simply sit on a support; it enters, grips, and transforms the fabric. Students can therefore investigate transparency, drape, contraction, edge behavior, density, and spatial responsiveness through a material system rather than through surface styling alone. The technique can be relevant to garments, wearable objects, membranes, screens, acoustic or spatial textiles, and installations, but a proposal should follow what the material demonstrably does.

The movement from technical sample to design proposition is a further learning step. Material experimentation generates evidence, but that evidence must be interpreted and translated deliberately into a contemporary design question. Design-research literature similarly positions materials as active generators of design knowledge and material experience rather than as a merely preliminary stage of styling [21,22]. In this way, a historical technique becomes a resource for design development rather than a decorative reference to heritage.

6. TWO-STAGE PEDAGOGICAL SEQUENCE: ART-STUDIO WORKSHOPS AND COURSE-BASED DESIGN DEVELOPMENT

The educational sequence was realized within the Slovenian Textile School activity of AlpTextyles, an Interreg Alpine Space project concerned with heritage-sensitive, circular, and innovative Alpine textile value chains [23,24]. The sequence comprised two linked stages. First, students learned wet-felting and nuno-felting techniques in workshops led by artisan Anja Musek at her AMUSE art studio in Škofja Loka. Second, they continued in the first-year Textile Techniques course in the Fashion and Textiles program at the Faculty of Design, where the acquired techniques were developed through individual research and artistic interpretation. AIR / ZRAK, the publicly announced theme of BIEN 2025, provided the conceptual framework for this second stage [25]. It was a biennial theme rather than a narrowly prescribed course brief: students formulated their own artistic-conceptual responses to air.

The initial technical workshops were led by artisan Anja Musek at her AMUSE art studio in Škofja Loka. Students worked with prepared wool and lightweight textile substrates supplied through the studio, learning fiber orientation, layer construction, wetting, soap application, rubbing, rolling, fulling, and nuno-felting processes. The workshop documentation does not distinguish specific wool grades or substrate compositions; the materials are therefore reported only at the level documented in the teaching record. Moving from the classroom into the practicing artist's studio was a situated feature of this teaching case: technique was encountered within an active artistic practice, including Musek's account of material decisions, iterations, and artistic intentions. This observation is descriptive rather than an independently evaluated effect of the studio setting. The workshops were not a comparative study of regional wool types or local supply chains.

The evidence base consists of workshop photographs, student-generated sample sets, process notes, the lecturer's field notes, and the spatial works submitted for assessment in the first-year Textile Techniques course. The lecturer, who is also the author, selected the samples and works discussed here as illustrative of a range of observed outcomes, including technically resolved samples and instructive failures. This collection documents process and outputs, but it cannot isolate causal learning effects from the wider educational context. The selection is illustrative rather than statistical and is consistent with the practice-based purpose of the paper.

The first phase established a shared technical vocabulary at Musek's art studio. Students handled prepared wool, considered fiber direction and layer construction, and observed how wetting, soap, rubbing, rolling, and fulling progressively changed the material. The teaching emphasis was diagnostic rather than merely demonstrative: students were asked to identify when fibers remained loose, when the surface started to hold, when pressure could be increased, and when shrinkage became irreversible. Figure 2 documents the fiber layout and rolling/fulling stages through which these changes were made visible.

Figure 2: Wet-felting workshop at Anja Musek's AMUSE art studio, Škofja Loka: (a) fiber layout before wetting; (b) rolling and fulling. Photographs: author archive.

Figure 3 documents the second workshop phase, which moved from basic control to comparative material experimentation. Students produced and reviewed samples that tested

density, transparency, openings, edges, layering, and the relation between wool and lightweight fabrics. In the nuno-felting exercises, the focus was on comparing fiber-fabric assemblies: how much the substrate contracted, where the fibers migrated, which areas remained open, and how the material responded when lifted, folded, or suspended. Photographs, sample sets, and process notes were treated as design evidence rather than as administrative records.

Figure 3: Nuno-felting workshop at artisan Anja Musek's AMUSE art studio in Škofja Loka: (a) students test wool-fabric assemblies, fiber distribution, and surface variation; (b) students review lightweight and translucent nuno-felted samples. Photographs: author archive.

Following the technical workshops, students continued with an extended material and structural investigation. This stage was not random or merely expressive experimentation. Each student constructed a personal sample set by systematically varying fiber quantity, directional layout, layer construction, density, transparency, openings, edge treatment, fabric substrate, contraction, and drape. The purpose was to generate a sufficiently broad body of material evidence before selecting a final spatial proposition. Working in relation to AIR / ZRAK, BIEN 2025's theme, students evaluated their sample sets and further developed those that most convincingly expressed their own conceptual interpretation of air. The selected material findings became the basis for individual artistic-conceptual spatial textile works. The lecturer guided the translation from sample evidence to spatial proposition, distinguishing unresolved technical failures, where a sample did not hold and offered no further design information, from productive failures, where uneven shrinkage, an unplanned opening, or an asymmetric contraction could be reframed as a usable design finding. This sequence aligns with material-driven approaches in which systematic material exploration informs design development [21,22].

Figure 4 presents selected examples of the works later exhibited in Idrija as part of the international Textile Art Biennial BIEN 2025 [25]. Only selected works, rather than all student projects, were exhibited. Each exhibited spatial textile work measured 80 × 200 cm. The transition from workshop and course to public presentation created an additional requirement: material process, conceptual interpretation, and spatial form had to be communicated beyond the teaching setting.

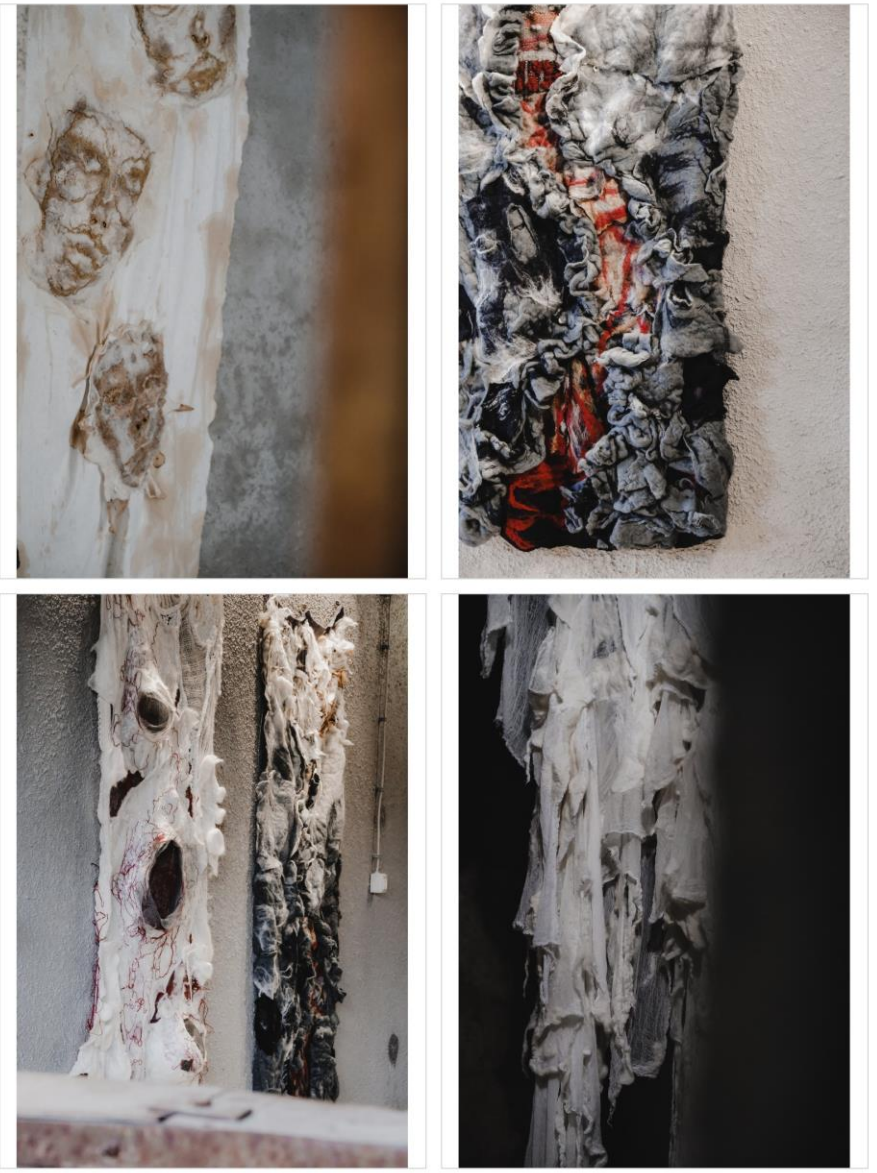

Figure 4: Selected 80 × 200 cm artistic-conceptual spatial textile works developed in the first-year Textile Techniques course in response to AIR / ZRAK, the theme of BIEN 2025. Lecturer: Asst. Prof. Almina Duraković Korošec. Exhibition photograph: Maša Pirc.

7. DISCUSSION

Wet felting is sometimes underestimated because it requires relatively little machinery. Low equipment intensity, however, does not mean intellectual simplicity. The technique requires sustained attention to fiber architecture, water, soap, pressure, temperature, friction, shrinkage, and time. Its pedagogical strength lies in the fact that these variables cannot be fully abstracted: students must encounter them through their hands and then articulate what they mean for the resulting textile.

The case also clarifies the relation between heritage and innovation. Heritage is not preserved by freezing a technique in historical form or by treating it as a decorative label. It becomes active when students learn the material logic of a technique, recognize the conditions in which it developed, and translate that logic responsibly into contemporary applications. In the present case, AIR / ZRAK, BIEN 2025's theme, provided a shared conceptual horizon within which students selected material evidence and developed questions of permeability, layered softness, tactility, openings, suspension, and spatial enclosure [25].

A central argument of this paper is that sustainability must be treated as a question of material responsibility rather than as an inherent property of wool or a quantified result of this case. The environmental and social implications of wool depend on animal husbandry, collection, washing, processing, transport, durability, use, and end-of-life routes. Research on wool valorization shows that logistics, processing capacity, heterogeneous fiber quality, and market conditions shape whether wool can be used effectively; these questions are particularly relevant where usable fleece is undervalued, stockpiled, or discarded [11-13]. Neither low equipment intensity nor wool's renewable origin is sufficient to establish environmental benefit. Although the workshops reported here did not compare local wool sources or conduct a life-cycle assessment, they provided a context in which students could ask more precise questions about material origin, preparation, intended use, and the consequences of design decisions.

The limitations of the account should remain clear. The photographs, samples, and final works document process and outputs, but they cannot establish causal learning effects independently of the wider educational context. The author's dual role as lecturer and analyst further reinforces the need to read the account as reflective and practice-based. A future study could add student reflection logs, interviews, pre/post prompts on material reasoning, or a systematic analysis of sample development. The present contribution is narrower: it offers a documented teaching sequence in which traditional knowledge, structured material investigation, and contemporary design development are deliberately connected.

8. CONCLUSION

Wet felting remains relevant to contemporary textile design education because it makes fundamental questions tangible: how fibers become structure, how the hand acquires

material judgment, how craft knowledge is transmitted, and how a historical process can generate contemporary design possibilities. In this teaching sequence, students first learned wet-felting and nuno-felting techniques at artisan Anja Musek's AMUSE art studio in Škofja Loka. They then applied the acquired techniques in the first-year Textile Techniques course in the Fashion and Textiles program, where systematic material and structural investigation informed the development of individual artistic-conceptual spatial textile works.

AIR / ZRAK, the theme of BIEN 2025, was interpreted through a deliberate research process rather than through arbitrary experimentation: students first created and evaluated personal sample sets, then selected and developed those that most clearly expressed their own interpretation of air. Only selected works, each measuring 80 × 200 cm, were later exhibited in Idrija as part of the international Textile Art Biennial BIEN 2025 [25]. The educational value of the method lies not in producing expert felt makers in one workshop, nor in making unqualified environmental claims. It lies in allowing students to experience how loose fibers, worked through one of the oldest textile technologies, can become self-authored spatial textile propositions that connect technique, tactile judgment, design intention, and contemporary textile expression.

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9. Međunarodna naučna konferencija
„**Savremeni trendovi i inovacije u tekstilnoj industriji**“
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ARTIFICIAL INTELLIGENCE IN FASHION DESIGN: GENERATIVE SYSTEMS, DIGITAL FASHION AND TRANSFORMATION OF THE CREATIVE PROCESS

Scientific paper
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ABSTRACT: *Artificial Intelligence (AI) is becoming one of the key drivers of innovation in the process of designing, manufacturing, and marketing fashion products. Contemporary fashion design is characterized by short development cycles, rapid changes in trends, and increasing demands for product personalization. Under such circumstances, designers face the need to process large amounts of information while simultaneously developing innovative aesthetic solutions. One of the most significant applications of AI in fashion is generative design. Generative systems use neural networks to create new visual content that is not a direct copy of existing products. This paper presents the application of AI in the development of a fashion collection using the AI assistant Grok. The results show that the use of artificial intelligence can accelerate the creative work process, but it cannot replace the creative process itself, which is based on knowledge and experience.*

Ključne reči: *Artificial Intelligence, fashion, generative design, AI tools.*

VEŠTAČKA INTELIGENCIJA U MODNOM DIZAJNU: GENERATIVNI SISTEMI, DIGITALNA MODA I TRANSFORMACIJA KREATIVNOG PROCESA

APSTRAKT: *Veštačka inteligencija (Artificial Intelligence – AI) postaje jedan od ključnih pokretača inovacija u procesu projektovanja, proizvodnje i plasmana modnih proizvoda. Savremeni modni dizajn karakterišu kratki razvojni ciklusi, brze promene trendova i rastući zahtevi za personalizacijom proizvoda. U takvim okolnostima dizajneri se suočavaju sa potrebom da obrađuju velike količine informacija i istovremeno razvijaju inovativna estetska rešenja. Jedna od najznačajnijih primena AI u modi jeste generativni dizajn. Generativni sistemi koriste neuronske mreže kako bi kreirali nove vizuelne sadržaje koji nisu direktne kopije postojećih proizvoda. U ovom radu je prikazana primena AI u razvoju modne kolekcije korišćenjem asistenta Grok. rezultati pokazuju da primena veštačke inteligencije može ubrzati proces kreativnog rada, ali da ne može zameniti sam kreativni proses iza koga stoji znanje i iskustvo.*

Ključne reči: *veštačka inteligencija, moda, genrativni dizajn, AI alati.*

1. INTRODUCTION

The contemporary development of digital technologies has significantly influenced the transformation of creative industries, with the fashion industry occupying a particularly prominent position. Artificial intelligence (AI) has become one of the key drivers of innovation in the design, production, and marketing of fashion products. Through the integration of machine learning algorithms, generative models, and big data analytics, AI enables designers to make more efficient decisions, enhance creative processes, and gain a deeper understanding of consumer needs.

Contemporary fashion design is characterized by short development cycles, rapidly changing trends, and increasing demands for product personalization. Under such conditions, designers face the challenge of processing vast amounts of information while simultaneously developing innovative aesthetic solutions. Artificial intelligence serves as a tool that bridges the creative process with a data-driven analytical approach, enabling more informed and efficient design practices.

2. THE WAY ARTIFICIAL INTELLIGENCE INTERPRETS FASHION

For a human designer, fashion design is a creative process inspired by culture, emotions, social change, and personal experience. In contrast, AI perceives a garment as a combination of attributes, including silhouette, proportions, cut, colors, textures, materials, decorative elements, and the ways in which these features appear across a large number of existing examples. By analyzing millions of images, fashion collections, and consumer behavior data, AI algorithms learn the relationships between individual stylistic elements and generate new combinations that are statistically meaningful.

In other words, while a human designer may create a dress inspired by Mediterranean architecture or a childhood memory, AI analyzes the characteristics of the Mediterranean style, its dominant colors, shapes, and textures, and then generates visual proposals that correspond to the specified parameters. For this reason, artificial intelligence is often described as a system that "recognizes patterns" rather than one that possesses creative intuition [1].

Based on this information, AI constructs mathematical models that describe the relationships between different design characteristics. When tasked with generating a new design, the system does not create from personal experience or inspiration; instead, it combines patterns learned from existing data.

This approach differs significantly from the human creative process. A fashion designer may draw inspiration from a work of art, a social event, or personal emotions, whereas AI identifies statistical regularities and generates new combinations based on previously analyzed examples.

3. GENERATIVE DESIGN AS A NEW PARADIGM OF CREATIVITY

One of the most significant applications of AI in the fashion industry is **generative design**. Generative systems use neural networks to create new visual content that is not a direct copy of existing products.

In the traditional design process, a designer produces numerous sketches before selecting the most successful solution. Generative artificial intelligence enables the creation of hundreds or even thousands of design variations within a very short period. The designer then assumes the role of curator and creative decision-maker, selecting, modifying, and further developing the most promising concepts. Such systems make it possible to explore a wide range of creative directions in a limited time, significantly accelerating the initial stage of collection development.

This process is transforming the role of the designer. Instead of independently generating every design idea, the designer guides a system that produces a large number of potential solutions. As a result, creativity is partially shifted from the act of creation itself toward the processes of selection, interpretation, and evaluation of AI-generated outcomes. [2]

Generative models can create new garments based on a text prompt, a sketch, or a mood board. For example, a designer may enter a prompt such as *"an oversized beige linen blazer with dropped shoulders,"* and the system can generate dozens of visual concepts within seconds. In addition to text prompts, designers can also use sketches or photographs as input. Based on the provided reference, AI creates a realistic visualization of the garment on a virtual model under specified conditions. Furthermore, conceptual designs can be generated by combining images with textual descriptions or simply by providing a mood board as a source of inspiration (Figure 1) [3].

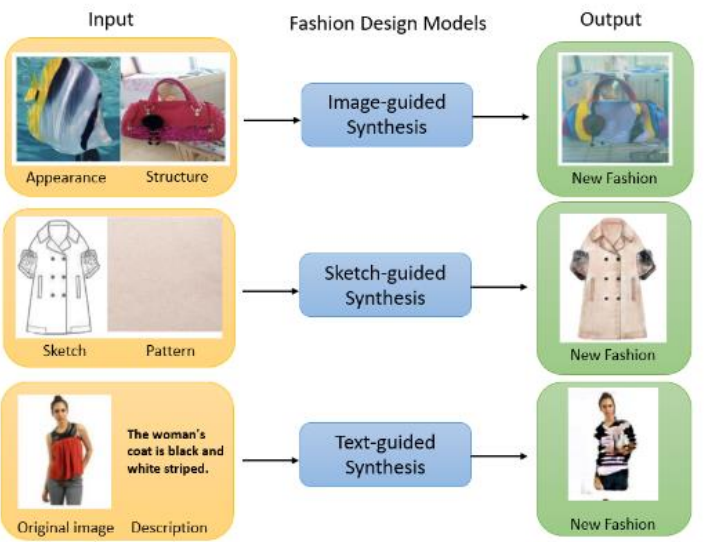

Figure 1: Examples of generative design

3.1. AI Tools for Generative Fashion Design

In contemporary fashion design practice, several key AI tools are widely used to generate sketches and visual concepts. Among the most prominent are Midjourney, DALL·E, Stable Diffusion, and Adobe Firefly.

Midjourney is frequently used to create highly aesthetic and conceptual fashion illustrations, making it particularly valuable during the inspiration and collection development stages. DALL·E enables the precise generation of fashion items based on detailed text prompts and is well suited for the iterative exploration and refinement of design ideas. Stable Diffusion, as an open-source model, offers greater control over the image generation process and is often employed in professional design studios to develop customized models tailored to specific fashion styles. Adobe Firefly integrates with professional design software such as Adobe Photoshop and Adobe Illustrator, allowing AI-generated elements to be incorporated directly into established design workflows [4].

Together, these tools form the foundation of the contemporary digital fashion design ecosystem, where the creative process is accelerated and expanded through the automated generation of visual concepts.

In addition to these professional platforms, numerous AI tools offer free access with limited functionality. Popular examples include Grok AI Assistant, Google Gemini, and ChatGPT. While all of these platforms provide a free tier, unrestricted access to their advanced features typically requires a paid subscription.

3.2. The Role of the Designer in the Generative Design Process

In the context of generative design, the role of the fashion designer is undergoing a significant transformation. The designer is no longer solely the creator of every sketch but instead becomes the creative director of the system, defining the generation parameters, interpreting the results, and selecting the most successful design solutions.

This model is often described as a **human-in-the-loop** approach, in which humans and artificial intelligence collaborate throughout an iterative creative process. The designer provides the initial concept or design brief, AI generates multiple variations, and the designer then evaluates, refines, and further develops the most promising concepts. In this way, the creative process becomes collaborative and dialogic rather than strictly linear.

3.3. From AI-Generated Sketch to Technical Pattern

One of the most important aspects of contemporary generative fashion design is the transition from a visual sketch to the technical realization of a garment. AI-generated images are no longer used solely as sources of inspiration; they are increasingly becoming a foundation for the development of garment patterns and technical documentation.

In advanced digital design systems, such as CLO 3D and Browzwear, it is possible to transform 2D visual concepts into 3D garment models. These systems enable the simulation of materials, fabric drape, and garment behavior on a virtual body. Based on an AI-generated sketch, a designer can develop an initial pattern, which can then be digitally tested and refined. [5]

The process of transforming a sketch into a pattern requires the interpretation of visual elements such as seam lines, sleeve construction, panel arrangement, and garment volume. Although artificial intelligence can provide initial construction guidelines, the final technical development still requires the expertise of a fashion pattern maker or garment constructor.

This hybrid approach significantly reduces product development time, as part of the experimental phase is transferred into a digital environment before physical production begins.

3.4. Applications in the Fashion Industry

n the contemporary fashion industry, generative AI systems are applied across various stages of product development. During the **concept development** phase, AI generates a wide range of visual directions and creative possibilities. In the design phase, these concepts are further developed into concrete garment models, while in the production phase they serve as a foundation for technical documentation and manufacturing preparation.

Major fashion companies use these systems to accelerate collection development and reduce prototyping costs. Instead of producing a large number of physical samples, designers can first test and refine ideas within a digital environment, which enables greater efficiency, faster decision-making, and more sustainable production processes.

3.5. Limitations of Generative Fashion Design

Although generative artificial intelligence offers significant advantages, it also has certain limitations. AI systems depend on the data on which they are trained, meaning they may reproduce existing aesthetic patterns and styles without a deeper understanding of the cultural context of fashion.

Furthermore, generated designs often require additional human intervention in order to be adapted to technical and production standards. AI can create visually appealing concepts, but it does not always guarantee their structural feasibility or practicality in garment construction.

4. AI AS A TOOL FOR FASHION TREND FORECASTING

Trend forecasting represents one of the most important activities within the fashion industry. Traditionally, fashion predictions were based on the work of experts who analyzed fashion shows, artistic movements, social changes, and consumer behavior.

Artificial intelligence significantly transforms this process. Today, algorithms can analyze:

- social media posts,
- influencer images,
- users’ online search data,
- sales data,
- fashion blogs and magazines,
- content from fashion events.

Such systems enable the identification of changes in consumer preferences before they become dominant in the market. For example, the frequent appearance of certain colors, materials, or silhouettes in the digital environment may indicate emerging fashion trends. This approach allows companies to reduce production risks and optimize the development of future collections [6].

5. PERSONALIZATION AND DIGITAL TRANSFORMATION OF THE CUSTOMER EXPERIENCE

A very common application of artificial intelligence in the fashion industry is the personalization of products and services. AI systems analyze individual user data, including previous purchases, clothing preferences, body characteristics, and digital behavior.
Based on this information, it is possible to generate personalized recommendations or even create garments tailored to a specific user. This process represents a shift from mass production toward a model of mass customization, in which products are adapted to the specific needs and preferences of each individual customer [7].

6. SUSTAINABILITY AND PRODUCTION OPTIMIZATION

The fashion industry faces significant environmental challenges, including overproduction and textile waste. Artificial intelligence contributes to sustainability through the optimization of pattern-making processes, accurate demand forecasting, and the reduction of production surpluses.
Furthermore, AI systems enable the analysis of the environmental characteristics of materials and the recommendation of more sustainable alternatives, supporting the development of circular fashion practices. [8] By creating digital samples and garment prototypes, greater efficiency can be achieved without the unnecessary consumption of time and resources required for producing physical clothing prototypes.

7. ADVANTAGES AND DISADVANTAGES OF USING AI IN FASHION DESIGN

Advantages
• Acceleration of the creative process
AI enables designers to generate a large number of conceptual solutions within a short period of time. It saves time when transferring ideas onto paper or digital platforms and allows easy modification of aesthetic and functional parameters of garments. Designers can quickly experiment with different shapes, materials, colors, and design directions.
• Visualization of garments before production
AI enables the visualization of garments on realistic digital models within predefined environments, under specific lighting conditions, and with selected materials before the physical product is created. While the use of CAD systems and 3D avatars requires

knowledge and application of specialized tools, generative design allows product visualization through simpler interaction using text prompts or image-based input.

• Environmental benefits

Through digital management of the garment development process, negative environmental impacts can be reduced, as physical waste generated during the early design and prototyping stages is significantly minimized. Digital samples and virtual prototypes reduce the need for unnecessary material consumption.

Disadvantages

• Lack of emotions and personal expression

Every form of art is based on emotions and the artist's personal experience, which represents the essence of creativity and enables the transfer of feelings to the audience. AI relies on algorithms and logical processing, which may reduce the emotional sensitivity, individuality, and personal expression of the designer.

• Aesthetic homogenization

There is a risk that AI, relying on existing trends and previously analyzed data, may lead to greater uniformity in design and a reduction in originality. Generated concepts may increasingly reflect dominant patterns rather than completely new creative approaches.

• Copyright and authorship issues

One of the key questions regarding AI-generated design is: who is the author of the final result? Is it the designer, the company, or the algorithm itself? Since AI systems learn from existing works, concerns also arise regarding potential copyright infringement and the use of protected creative content.

• Potential loss of creative professions

There is concern that excessive automation could reduce the need for certain creative roles, especially during the early stages of the design process. At the same time, the development of new professions is expected, such as AI fashion designer, digital fashion curator, generative design specialist, and virtual clothing developer.

• Data ethics and privacy

AI systems rely on large amounts of user data, which raises important questions regarding privacy, data protection, and the ethical use of personal information [9].

8. MATERIALS AND METHODS

For the purposes of this research, fashion sketches from a collection inspired by braids were used. After the concept of the braid as a visual and cultural code had been further developed, the next step in the process was its translation into specific visual forms. The creation of the initial sketches represented a critical moment in which the abstract idea was transformed into material shapes, lines, and rhythm. The sketches enabled experimentation with different compositions, structures, and patterns, serving as a foundation for the further development phase of the design.

The sketches were created on paper using various techniques, including pencil, markers, and colors, which allowed for the exploration of textures, details, and different variations of the braid motif. Their purpose was not only to convey the basic form of the motif but

also to examine the ways in which it could be adapted to a contemporary textile and fashion context (Figure 2).

Figure 2: Models sketches: a - Model 1, b - Model 2, - c - model 3, d - model 4, e - model 5.

A fashion designer transforms their ideas into sketches, creating a visual representation of the concept. The appearance of the model in the sketches depends on the designer's knowledge and experience in translating their vision onto paper. In many cases, additional explanations and technical drawings are required in order for the garment to be accurately produced under real-world conditions.

By applying a generative form of artificial intelligence through an **image-to-image** method, a realistic model of the garment was created, displayed on a virtual model walking on a fashion runway. For this purpose, the Grok AI tool was used (Figure 3).

Figure 3: Generated models by GROK based on model sketches from Figure 2: a - Model 1, b - Model 2, - c - model 3, d - model 4, e - model 5.

In this way, additional information about the garment that needs to be created can be obtained. This includes how the garment will fit on the body, which materials should be used, where the fastening system should be positioned, and other important construction

details. In this particular case, the greatest challenge was the integration of the braid elements — how they would appear on a realistic model, how they would fall and move, and how they would behave during wear.
In this process, the generative artificial intelligence model transformed the image of the garment on a virtual model into a video representation of the model walking on a fashion runway. In this way, the designer's sketch was developed in greater detail, providing designers, pattern makers, and garment manufacturers with valuable information regarding the production process, material selection, garment construction, placement of darts, as well as the method of creating and attaching the braid elements to the garment.

9. RESULTS AND DISCUSSION

After developing the model using the generative AI system in the Grok program and analyzing the visual information provided by AI, the next step was the selection of materials. Two types of fabrics were chosen: burgundy twill, characterized by a higher fabric weight and greater bending stiffness, and a lighter plain-weave satin, with lower stiffness and surface weight, providing better draping properties.
Patterns were developed, and the dresses were constructed as shown in Figure 4. The completed dress models were presented at the 49th Sarajevo Fashion Week. The collection consists of six thematic designs and is titled "Crimson Braid."

a

b

c

d **e**

Figure 4: Collection of dresses at Sarajevo fashion week: a - Model 1, b - Model 2, - c - model 3, d - model 4, e - model 5.

Creating Model C was the most challenging task, as it involved the construction of unconventional structures and the complex layered composition of the garment. This dress model represents a contemporary sculptural interpretation of form, material, and movement, emphasizing the artistic transformation of the traditional braid motif into a futuristic fashion expression.

The garment is designed in a deep burgundy shade, creating an impression of elegance, strength, and warmth, while the symbolism of the color reflects energy and passion. The silhouette is characterized by an asymmetrical cut, with one shoulder exposed and the other supported by a delicate shoulder strap that extends into an organically curved neckline across the bust. This design element introduces dynamism to the upper part of the garment, creating a sense of fluidity and movement despite its firm, architectural construction.

Around the waist and hip area, the silhouette expands into a series of three-dimensional curves that create a structural frame around the body, resembling armor or an architectural shell. This sculptural composition enhances the expressive character of the garment and reinforces its bold, avant-garde aesthetic.

Figure 5 presents the development process of Model C, from the initial sketch, through the AI transformation phase, to the final realized garment.

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a b c

Figure 5: Development of the model c: a - Model sketch, b - Generated model, - c - Real model.

10. CONCLUSION

Artificial intelligence represents a key factor in the transformation of contemporary fashion design. Its application encompasses all stages of the creative process — from idea generation and trend forecasting to production and marketing presentation.

Generative fashion design represents a new stage in the evolution of the creative process within the fashion industry. Artificial intelligence enables the rapid generation of visual concepts, exploration of a wide range of design directions, and optimization of the transition from an initial concept to technical realization.

However, despite technological advancements, the central role continues to belong to the designer, who interprets, selects, and shapes the generated results. The future of fashion design is based on the synergy between human creativity and algorithmic intelligence, where AI functions as a tool for expanding creative possibilities rather than replacing the creative process.

Today, artificial intelligence is becoming integrated into all aspects of human life. It represents an inevitable part of the future, both in personal and professional contexts. The key question is how it will be used. Without the knowledge and experience inherent to every profession, which individuals acquire through learning and practice, AI remains limited. It cannot provide solutions beyond the ability of the user to define, direct, and meaningfully apply its capabilities.

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DIGITAL 3D GARMENT DEVELOPMENT PROCESS: FROM CONCEPT TO VIRTUAL PROTOTYPE

Professional paper
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ABSTRACT: *The digital transformation of the apparel industry is increasingly driven by the integration of 2D pattern development and 3D virtual simulation technologies. This study focuses on the digital 3D garment development process using VStitcher (Browzwear), presenting a structured workflow from the initial design concept to the final virtual prototype. The proposed approach emphasizes the transition from traditional physical sampling to digital prototyping, enabling improved efficiency, faster design interactions, and reduced material consumption. The workflow includes 2D pattern construction, material definition and mapping, virtual garment assembly, 3D simulation, and fit evaluation on a digital avatar. The results demonstrate that integrating 2D and 3D environments creates a continuous feedback loop that supports iterative refinement of design parameters and early detection of construction and fit issues. The study further confirms that virtual prototyping, supported by styling tools, enhances garment evaluation by enabling advanced manipulation and simulation of manual fitting adjustments. This contributes to reduced physical sampling, improved development accuracy, and increased workflow efficiency. However, simulation accuracy remains dependent on precise pattern construction, material parameter definition, garment complexity, and user expertise, while certain tactile fabric properties cannot yet be fully replicated digitally. Overall, the study demonstrates that 3D garment development systems such as VStitcher provide a robust methodological framework for more efficient, accurate, and sustainable apparel product development in both industrial and educational contexts.*

Keywords: *digital garment development, 3D apparel design, virtual prototyping, VStitcher (Browzwear), garment simulation.*

DIGITALNI 3D PROCES RAZVOJA ODEĆE: OD KONCEPTA DO VIRTUELNOG PROTOTIPA

APSTRAKT: *Digitalnu transformaciju industrije odeće sve više pokreće integracija 2D razvoja krojeva i 3D tehnologija virtuelne simulacije. Ova studija se fokusira na proces digitalnog 3D razvoja odeće korišćenjem VStitcher-a (Browzwear), predstavljajući*

strukturirani tok rada od početnog koncepta dizajna do finalnog virtuelnog prototipa. Predloženi pristup naglašava prelazak sa tradicionalnog fizičkog uzorkovanja na digitalno prototipiranje, omogućavajući poboljšanu efikasnost, brže interakcije sa dizajnom i smanjenu potrošnju materijala. Tok rada uključuje 2D konstrukciju krojeva, definisanje i mapiranje materijala, virtuelno sklapanje odeće, 3D simulaciju i procenu pristajanja na digitalnom avataru. Rezultati pokazuju da integracija 2D i 3D okruženja stvara kontinuiranu povratnu spregu koja podržava iterativno usavršavanje parametara dizajna i rano otkrivanje problema sa konstrukcijom i pristajanjem. Studija dalje potvrđuje da virtuelno prototipiranje, uz podršku alata za stilizovanje, poboljšava procenu odeće omogućavajući naprednu manipulaciju i simulaciju ručnog podešavanja pristajanja. Ovo doprinosi smanjenju fizičkog uzorkovanja, poboljšanoj tačnosti razvoja i povećanoj efikasnosti toka rada. Međutim, tačnost simulacije i dalje zavisi od precizne konstrukcije kroja, definicije parametara materijala, složenosti odeće i stručnosti korisnika, dok se određena taktilna svojstva tkanine još uvek ne mogu u potpunosti digitalno replicirati. Generalno, studija pokazuje da 3D sistemi za razvoj odeće, kao što je VStitcher, pružaju robustan metodološki okvir za efikasniji, precizniji i održiviji razvoj proizvoda odeće, kako u industrijskom tako i u obrazovnom kontekstu..

Ključne reči: *digitalni razvoj odeće; 3D dizajn odeće; virtuelno prototipiranje; VStitcher (Browzwear); simulacija odeće.*

1. INTRODUCTION

The fashion industry is undergoing a profound digital transformation driven by advances in computer-aided design (CAD), computer-aided manufacturing (CAM), simulation tools, immersive visualization technologies, and, more recently, artificial intelligence (AI). These developments have fundamentally reshaped the garment development process, shifting traditional workflows based on manual sketching, physical patternmaking, and iterative sampling toward digitally integrated approaches. Within this context, 3D garment development has emerged as a key innovation, enabling garments to be designed, simulated, and evaluated in virtual environments before physical production [1]-[3]. The integration of AI further enhances these capabilities through automated design generation, predictive fit analysis, and optimization of material and construction parameters, improving efficiency and decision-making throughout the development cycle [4], [5].

A major advantage of the 3D garment development process is its ability to support a structured workflow from concept creation to virtual prototyping. Using specialized software, designers can develop digital patterns, define material properties, assemble garments, and evaluate fit and appearance on digital avatars. This approach facilitates rapid design iterations, reduces development time and costs, and minimizes dependence on physical samples [6]. The process typically consists of interconnected stages, including concept development, digital pattern construction, 2D/3D garment assembly, fabric simulation, and virtual fit evaluation. Through continuous feedback between these stages,

design, fit, and construction parameters can be iteratively refined, leading to shorter development cycles (by 50-75%) and improved product accuracy [7]-[11].
Beyond efficiency gains, 3D fashion design contributes to sustainability by reducing material consumption, textile waste, and the environmental impacts associated with physical sampling (Figure 1). Virtual sampling decreases the use of water, dyes, and chemicals and can reduce emissions by up to 97% [7], [13]. In addition, digital technologies enhance customization, visualization, and collaboration, while supporting faster time-to-market and more flexible product development processes [13], [13].

Figure 1: Key impacts and benefits of 3D fashion design in apparel development

Despite these benefits, several challenges remain. The accuracy of virtual simulations depends on the precise representation of material properties, garment construction details, and user expertise. Complex material behavior and certain tactile characteristics cannot yet be fully replicated in digital environments, limiting the complete replacement of physical prototyping. Furthermore, successful implementation requires not only technological infrastructure but also effective workflow integration and a strong foundation in patternmaking and garment construction principles [15], [16].
Although the benefits of 3D garment development are widely recognized, there remains a need for a clearer methodological understanding of how the complete digital workflow is

structured and implemented in practice. Therefore, the aim of this study is to analyze the digital 3D garment development process – from concept to virtual prototype – within a structured and iterative framework using VStitcher (Browzwear). Specifically, the study examines the key stages of the workflow, evaluates the role of enabling technologies in design optimization and workflow integration, assesses the effectiveness of virtual prototyping in reducing physical sampling, and identifies the principal limitations and factors influencing successful implementation. The findings contribute to a better understanding of digital garment development methodologies and support their application in both industry and education.

2. RESEARCH METHODOLOGY

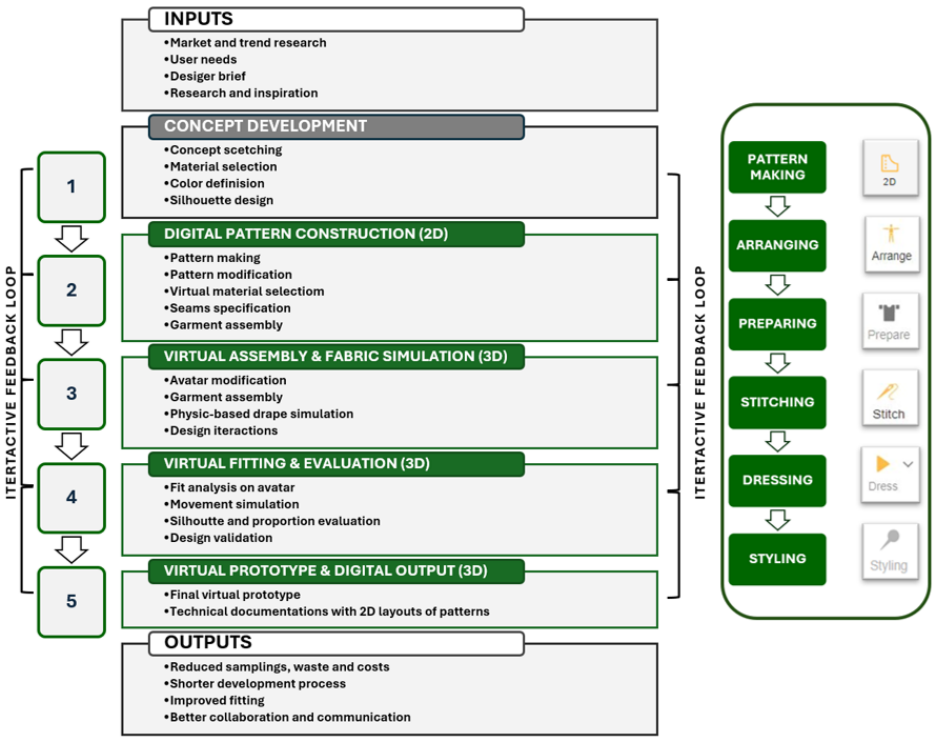
2.1. Method

Various software solutions support digital garment development, ranging from traditional 2D CAD systems, such as Gerber AccuMark and Lectra Modaris, to fully integrated 3D systems, including CLO3D, V-Stitcher (Browzwear), Optitex, and Style3D Studio. While traditional CAD systems primarily focus on pattern construction and grading, advanced 3D systems integrate digital patternmaking, fabric digitalization, virtual fitting, and garment simulation into a unified environment. These capabilities enable realistic evaluation of garment fit, drape, and construction prior to physical production, thereby reducing the need for physical samples and improving development efficiency. Among these solutions, V-Stitcher provides advanced fabric simulation through its Fabric Analyzer (FAB), which incorporates measured material properties to enhance simulation accuracy and support reliable virtual prototyping.

Based on these capabilities, V-Stitcher (Browzwear) was selected as the system for this study. The digital 3D garment development process – from concept development to virtual prototyping – was examined using the conceptual framework developed in this study. As illustrated in Figure 2a, the framework defines the key stages of the workflow and their iterative interactions, while Figure 2b presents its practical implementation within the VStitcher environment.

Figure 2(a) presents the overall workflow as a structured, iterative process that progresses from initial inputs to final outputs. The process begins with design inputs, including market and trend analysis, user requirements, and creative inspiration, which inform the concept development. This is followed by digital pattern construction in 2D, where garment patterns are created and prepared for simulation through the selection of virtual materials and seam specifications during garment assembly. The workflow then advances to 3D virtual assembly and fabric simulation, enabling a realistic representation of garment construction and material behavior. In the next stage, virtual fitting and evaluation are performed to assess fit, movement, and proportions on digital avatars. The process concludes with the generation of a virtual prototype and digital outputs, including technical documentation and production-ready data. As indicated by the feedback loops, all stages are interconnected, enabling continuous refinement and iterative optimization throughout

development. The main outcomes of this workflow include sampling, shorter development time, improved fit accuracy, and enhanced communication.
Figure 2(b) illustrates the operational implementation of this framework in the VStitcher (Browzwear) environment. The workflow is organized into sequential modules – pattern making, arranging, preparing, stitching, dressing, and styling – which correspond to the stages defined in the conceptual model. This alignment demonstrates how theoretical principles of digital garment development are translated into practice using specialized 3D software tools, enabling a streamlined and integrated workflow from concept to virtual prototype.



a) b)

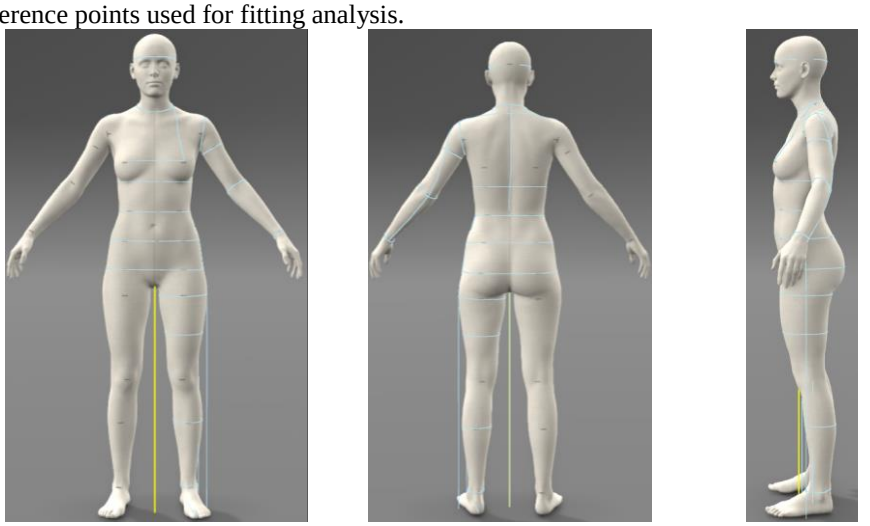
Figure 2: Conceptual framework of the digital 3D garment development process (a), and enables possibilities in VStitcher (Browzwear) (b)

Overall, the figure highlights the relationship between the conceptual framework and its practical implementation, emphasizing the role of digital technologies in enabling an efficient, iterative, and simulation-driven approach to garment development.

2.2. Materials

Digital avatar

The digital avatar Olivia, used for T-shirt simulation, is presented in Figure 3. The avatar was configured with symmetric positioning and the original body resolution, and human friction was enabled to ensure realistic interaction between the garment and the body during virtual fitting. Figure 3 illustrates the avatar Olivia with a fit marker texture from multiple views: front, back, and left, providing a clear visualization of body geometry and the reference points used for fitting analysis.



a) b) c)

Figure 3: Avatar Olivia in fit markers texture: a) front view, b) back view, c) left view

General body measurements of the digital avatar Olivia are presented in Table 1. The Table 1 provides a detailed overview of the avatar's configuration for size EU38, including general settings such as:

- body resolution – original,
- texture – fit markers,
- avatar friction – human.

The anthropometric data are organized into three categories: general body measurements, upper body measurements, and lower body measurements. This structured dataset includes standardized body dimensions such as height, shoulder width, bust, waist, hip, and limb circumferences, ensuring an anatomically accurate digital representation of the human

body. These parameters enable consistent and reliable assessment of garment fit, proportion, and silhouette behavior within the virtual environment.

Table 1: General body measurements of the digital avatar Olivia

Category	Parameter	Unit	Value
General body measurements	Height	cm	168.0
	Head circumference	cm	54.4
	Neck circumference	cm	35.0
	Shoulder width	cm	36.2
	Nape-to-waist length	cm	40.8
Upper body measurements	Bust circumference	cm	88.0
	Underbust circumference	cm	74.6
	High point shoulder (HPS) to apex	cm	25.3
	Apex-to-apex distance	cm	18.8
	Waist circumference	cm	68.0
	Armhole circumference	cm	36.5
	Arm length	cm	53.6
	Elbow circumference	cm	23.1
	Wrist circumference	cm	15.0
	Bicep circumference	cm	27.1
Lower body measurements	High hip circumference	cm	83.8
	Hip circumference	cm	93.0
	Thigh circumference	cm	50.9
	Knee circumference	cm	31.0
	Knee height	cm	45.5
	Calf circumference	cm	32.6
	Ankle circumference	cm	23.2
	Inseam length	cm	80.0
	Outseam length	cm	107.5
	Foot length	cm	23.8

Garment product

A women’s T-shirt (EU38) with a simple construction – featuring a crew neckline, set-in short sleeves, a slim silhouette, and a rounded hemline – was selected as the garment model for this study (Figure 4). The T-shirt was chosen due to its widespread use in fashion collections and its relevance as a basic apparel item for evaluating digital garment development processes. Two color/material variations were developed: a solid white version and a green-striped version.

Figure 4 presents the developed T-shirt in both variants: solid white and green-striped, shown from multiple views (front, back, and side), enabling a comprehensive visualization of silhouette and construction details.

The white T-shirt was constructed using single-jersey knitted fabric for the main garment parts (front, back, and sleeves) in white color (Pantone 11-1001 TCX), while a 1×1 rib

knitted fabric was used for the neckband. The green-striped version was developed using single jersey jacquard knitted fabric with a green striped pattern (YKK 018 with dark green stripes) for the main parts, combined with a 1×1 rib knitted fabric for neckband in green color (YKK 018). These material combinations were selected to evaluate the influence of fabric structure and pattern on garment appearance and simulation behavior.

a) b) c) d)

Figure 4: Women's T-shirt in solid white color (a-c) and green stripes color (d): a) and d) front view, b) back view, c) left side view

The construction pattern pieces of the T-shirt are shown in Figure 5.

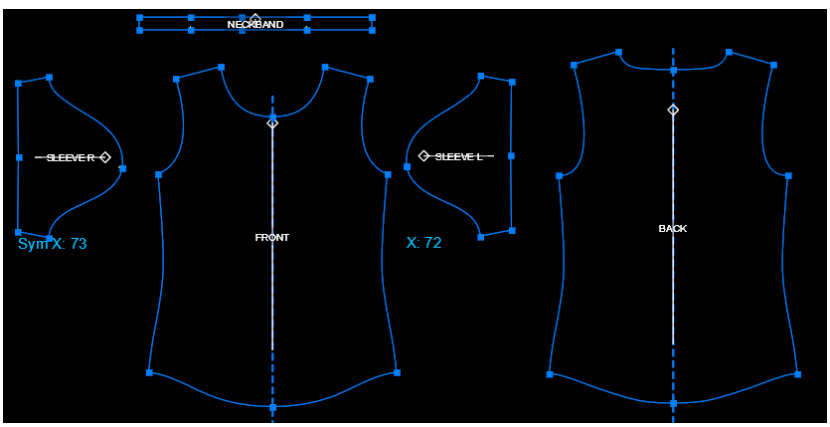
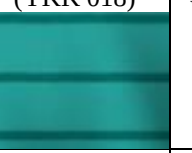


Figure 5: T-shirt construction pattern pieces – front, back, right sleeve, and left sleeve

Table 2 presents the main characteristics of the virtual materials used in the T-shirt simulation, organized by T-shirt part (front, back, sleeves, and neckband). Three knitted fabric types were defined: single jersey (plain), single jersey jacquard, and 1×1 rib. The

single jersey (plain) fabric was applied to the main parts of the white T-shirt (front, back, and sleeves) in white (Pantone 11-1001 TCX), while the single jersey jacquard fabric was used for the striped version in green (YKK 018) with dark green stripe detailing. The 1×1 rib fabric was assigned to the neckband in both variants, using white for the plain T-shirt and green (YKK 018) for the striped version.

Table 2: Main characteristics of the virtual materials used for the T-shirt simulation

Chacteristic	Unit	White (front, back, sleeves)	Green stripes (front, back, sleeves)	White/green (neckband)
Knit fabric	-	single jersey (plain)	single jersey jacquard	1x1 rib
Main color	-	white (Pantone 11-1001 TCX)	green (YKK 018) 	white (Pantone 11-1001 TCX)/green (YKK 018)
Fabric composition	%	cotton 100%	cotton 60%, polyester 40%	cotton 100%
Weight	g/m^2	180	180	270
Friction	-	0.2	0.2	0.2
Thickness	mm	0.76	0.80	1.00
Bend in width and length (WxL)	dyn*cm	114.47 x 124.64	25.98 x 11.74	31.46 x 334.96
Stretch in width and length (WxL)	N/m	259.73 x 446.42	107.34 x 39.24	24.86 x 608.90
Stretch linearity in width and length (WxL)	%	48.93 x 0	25.65 x 5	0 x 0
Shear	N/m	79.33	58.39	18.2
Shear linearity	%	27.16	34.67	68.5

The results show clear differences among virtual knitted fabrics. The single jersey jacquard fabric exhibits greater flexibility in the width direction and lower bending stiffness, which is consistent with typical material behavior [17]. The neckband material (1×1 rib), characterized by the greatest thickness, demonstrates higher bending resistance, particularly in the length direction, supporting its structural function in maintaining neckline stability. In tensile behavior, the single jersey (plain) fabric shows higher stretchability, especially in the length direction, indicating greater extensibility and recovery potential. Shear properties also vary among materials; the rib fabric exhibits the

lowest shear stiffness, making it highly deformable and particularly suitable for shaping and stabilizing the neck opening. Overall, this combination of these materials provides a balanced performance in terms of stability, elasticity, and comfort, which is essential for realistic virtual garment simulations and digital prototyping.
Silhouette variants of the women's T-shirt are presented in Table 3. These variants (Table 3) can be developed using the SmartDesign function in VStitcher (Browzwear), which enables the creation of different design options by modifying body fit, neckline shape, sleeve type, and hemline form.

Table 3: Main design differences among silhouette variants

Design element	Silhouette variants				
Body	Slim	Regular	Loose		
Neckline shape	Crew neck	Scoop neck	Boat neck	V neck	Deep V neck
Sleeve type	Short	Long			
Hemline from	Straight	Rounded			

Table 3 outlines the key garment design elements and their variations in silhouette and style considered in this study. It classifies four main design or structural components: body silhouette, neckline shape, sleeve type, and hemline form. The body silhouette is defined through slim, regular, and loose fits, representing progressively increasing ease and

garment volume. Neckline shape options include crew, scoop, boat, V-neck, and deep V-neck styles, reflecting variations in coverage and aesthetic expression. Sleeve options are categorized as short or long, corresponding to functional and seasonal requirements. Hemline forms are defined as straight or rounded, indicating differences in garment shape and visual flow. This typology enables systematic comparison and consistent parameterization in the analysis of garment design variations.

3. RESULTS AND DISCUSSIONS

The 3D garment development workflow in VStitcher (Browzwear) represents a structured and iterative process that integrates 2D pattern construction with 3D simulation and virtual fitting, enabling a continuous feedback loop between design and validation (Figure 2b). In line with the study objectives, the results are discussed through the main stages of the digital garment development process, the role of enabling technologies, the effectiveness of virtual prototyping, and the identified limitations.

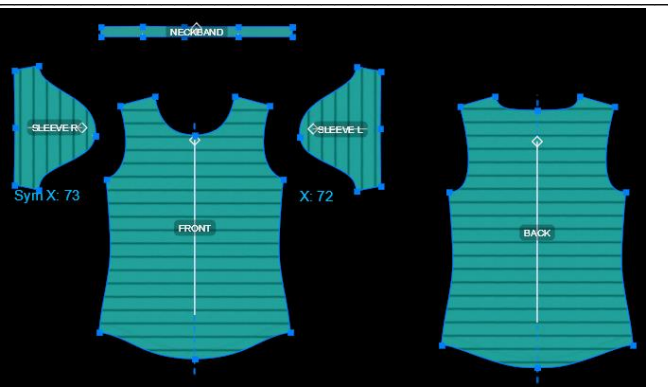
The process begins with translating the design concept into digital pattern pieces within the 2D workspace (Figure 6a). Pattern creation is performed either through direct digital drafting or by importing CAD files (.DXF, .AAMA, .ASTM). In practise, adapting existing base patterns with similar construction proved to be the most efficient approach, enabling faster development and more precise control of garment form and fit. This stage is essential for ensuring structural accuracy, including correct seam allowances, grainline orientation, and compliance with technical specifications, which form the foundation for reliable 3D simulation.

The critical aspect at this stage is material mapping on pattern pieces, particularly for fabrics with directional characteristics such as stripes or motifs. Accurate alignment is essential for maintaining aesthetic consistency and seam continuity, especially at key junctions between front, back, and sleeve parts. This was confirmed during virtual assembly and visualization (Figure 7e–h), where potential misalignment issues were identified early in the digital process.

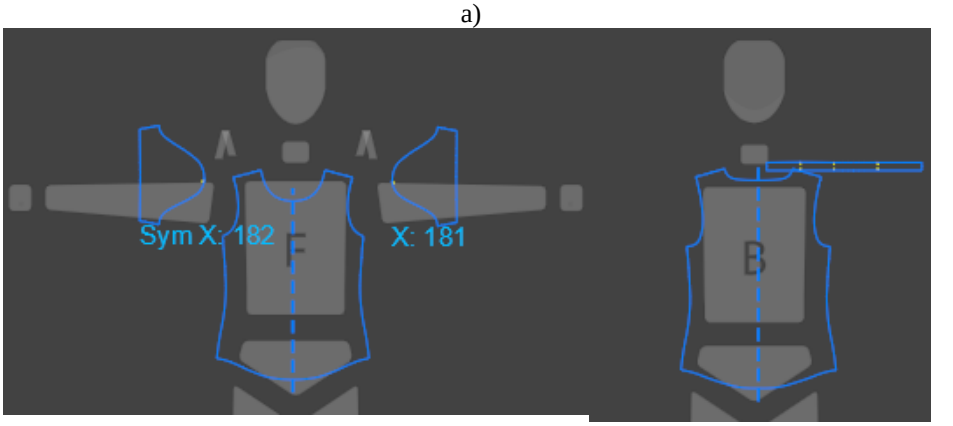
Following pattern development, the pattern pieces are organized in the 2D workspace according to grain line direction and arranged on the avatar in the 2D and 3D workspace for virtual fitting on the avatar (Figures 6b–6c). This bidirectional interaction between 2D and 3D environments demonstrates a strong workflow integration and supports continuos iterative refinement of design decisions.

The 3D avatar provides a multi-angle visualization (front, back, side, top, and bottom views), enabling early evaluation of symmetry, proportion, and spatial fit. Based on these assessments, pattern adjustments are iteratively performed in the 2D environment, including modifications of shape, ease distribution, and seam positioning. This feedback loop significantly reduces reliance on physical sampling and improves design efficiency.

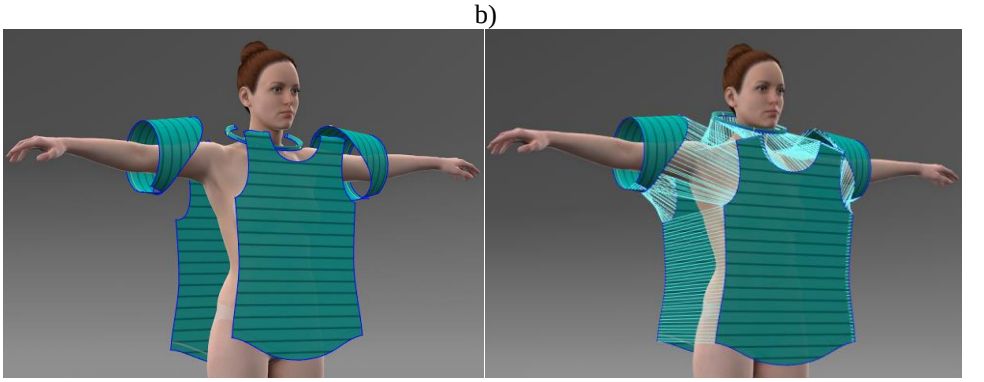
The stitching phase is defined digitally in the 2D environment, where seam connections and construction logic are established prior to simulation. Once assembled in a 3D environment (Figure 6d), the garment exhibits simulated realistic fabric behavior, including tension distribution, deformation, and drape interactions with the avatar body.



a)



b)



c) d)

Figure 6: 3D T-shirt development process in VStitcher: a) creating a pattern in 2D and positions of the materials on the pattern pieces, b) arranging in 2D, c) arranging in 3D, d) stitching in 3D (*Positions of avatar (b): F – front, B – back)*

The results indicate that virtual prototyping is effective for predicting garment fit and silhouette behavior prior to physical production. The final simulation (Figure 7) enables a comprehensive evaluation of garment aesthetics, movement, and structural balance. Additionally, fit refinement can be performed using styling tools that simulate the manual adjustments typically carried out on a physical mannequin. These tools allow advanced manipulation of the draped garment, including repositioning across different avatar poses, correcting drape issues in layered outfits, adjusting and locking pattern pieces, refining seam and stitch placement, and controlling internal garment parts such as pockets. Garments can also be repositioned if displaced during simulation, improving overall balance, appearance, and realism. Consequently, styling functions contribute significantly to achieving an accurate and optimized virtual fit before physical prototyping. Iterative adjustments based on simulation feedback further enhance design precision and reduce the need for multiple physical samples.

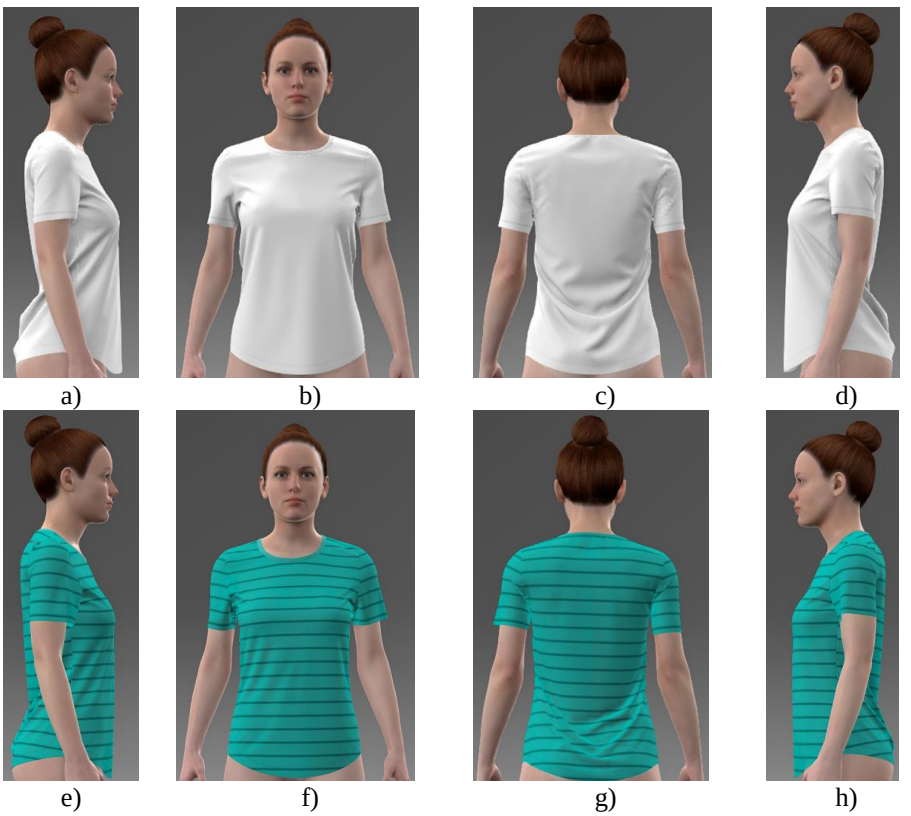
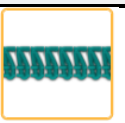
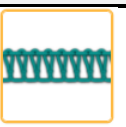


Figure 7: 3D T-shirt development process in VStitcher for white (a-c) and green-striped (e-h) variations during dressing and styling:
a) and e) right view, b) and f) front view, c) and g) back view, d) and h) left view

Seam characteristics and their structural implications are summarized in Table 4, where seam types defined according to ISO standards (ISO 301, ISO 401, ISO 514) are compared. The analysis highlights the influence of seam construction on garment stability, flexibility, and visual appearance, emphasizing the importance of accurate digital construction logic in the virtual environment.

Table 4: Type and main characteristics of the seams

Characteristics of the seam	Type of the seam			
	ISO 406		ISO 514	
	face	back	face	back
Texture of seam				
Line count	1		1	
Length, SPC	3.94		7.87	
Width, cm	0.51		0.32	
Space, cm	0.02		0.01	
Used stitches	Sleeve cuffs, bottom hem, and neckline topstitching		Side, shoulder, armhole, neckline seams	
Materials	polyester threads 25 tex in white and green colors			
**SPC – stitches per centimeter*				

Despite these advantages, several limitations were identified during the implementation of the digital workflow. The accuracy of virtual simulation strongly depends on precise pattern construction and accurate material parameter definition. In addition, the effectiveness of virtual prototyping is influenced by garment complexity and user expertise in both patternmaking and software operation. Complex garment structures may require additional manual adjustments, which can reduce workflow efficiency. Furthermore, although VStitcher provides advanced visualization capabilities, certain tactile and real-world fabric behaviors cannot yet be fully replicated in the digital environment.

4. CONCLUSION

This study analysed the digital 3D garment development process in VStitcher (Browzwear) for women's T-shirts within a structured, iterative framework from concept development to virtual prototyping. The results demonstrated that integrating 2D pattern construction, 3D simulation, and virtual fitting enables a continuous feedback loop that supports efficient design validation and systematic optimization throughout the garment development process.

The findings confirmed that accurate digital pattern construction and material mapping are critical factors influencing the quality of virtual simulation and the realism of garment appearance. The interaction between 2D and 3D work environments supports interactive

refinement of garment geometry, fit, seam positioning, and aesthetic properties, enabling early detection and correction of design inconsistencies prior to physical prototyping.

The study also demonstrated the effectiveness of virtual prototyping for evaluating garment fit, silhouette, drape behavior, and structural balance. The use of styling tools further enhanced the refinement process by enabling advanced manipulation of the garment and simulating manual fitting adjustments typically performed on physical prototypes. As a result, the digital workflow helps reduce the number of physical samples required, improves development accuracy, and increases process efficiency.

However, simulation accuracy remains dependent on precise pattern construction, correct definition of material parameters, garment complexity, and user expertise in both patternmaking and software operation. In addition, certain tactile and real fabric behaviors cannot yet be fully replicated in the virtual environment.

Overall, the study confirms that 3D garment development systems, such as VStitcher, have significant potential to improve product development process in both industrial and educational contexts. The presented workflow contributes to a clearer methodological understanding of digital garment development and supports further implementation of virtual prototyping technologies in sustainable and efficient apparel design practices.

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ENHANCING TEXTILE SCREEN PRINTING EDUCATION THROUGH MULTIMEDIA LEARNING APPROACHES

Scientific paper
DOI: 10.5937/CT_ITI26044K

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ABSTRACT: *Over the past decades, education has undergone significant transformations driven by digitalization, globalization and rapid technological development. Advances in internet technologies, multimedia systems and digital learning platforms have reshaped the ways knowledge is delivered, acquired and shared. Digital tools have evolved from supportive resources into essential components of contemporary pedagogical models, enabling flexible, student-centered, and practice-oriented learning environments.*
Within this framework, multimedia learning has proven to be an effective approach for teaching complex technical subjects. Multimedia learning occurs when learners construct mental representations through the integration of verbal and visual information, leading to improved comprehension compared to text-based instruction alone.
This paper presents a multimedia-based approach to teaching textile screen printing technology. The presented case illustrates how multimedia-supported instruction can improve the teaching and learning of textile screen printing and highlights the potential for applying similar approaches in other practical and process-oriented areas of graphic and textile engineering education.
Keywords: *Education, multimedia systems, digital learning textile, screen printing.*

UNAPREĐENJE OBRAZOVANJA U OBLASTI SITO ŠTAMPE NA TEKSTIL PRIMENOM MULTIMEDIJALNIH PRISTUPA UČENJU

APSTRAKT: *Tokom proteklih decenija obrazovanje je doživelo značajne transformacije pod uticajem digitalizacije, globalizacije i brzog tehnološkog razvoja. Napredak internet*

tehnologija, multimedijalnih sistema i digitalnih platformi za učenje promenio je načine na koje se znanje prenosi, usvaja i deli. Digitalni alati su evoluirali od pomoćnih sredstava do ključnih komponenti savremenih pedagoških modela, omogućavajući fleksibilna, studentima prilagođena i praktično orijentisana okruženja za učenje.
U okviru ovog koncepta, multimedijalno učenje se pokazalo kao efikasan pristup za podučavanje složenih tehničkih oblasti. Multimedijalno učenje podrazumeva da studenti formiraju mentalne modele integracijom verbalnih i vizuelnih informacija, što dovodi do boljeg razumevanja sadržaja u poređenju sa učenjem zasnovanim isključivo na tekstu.
Ovaj rad predstavlja multimedijalni pristup nastavi tehnologije sito štampe na tekstilu. Prikazani primer pokazuje kako nastava podržana multimedijalnim sadržajima može unaprediti proces podučavanja i usvajanja znanja iz oblasti tekstilne sito štampe, istovremeno ukazujući na mogućnosti primene sličnih pristupa u drugim praktično orijentisanim i procesno zasnovanim oblastima grafičkog i tekstilnog inženjerstva.

Ključne reči: *obrazovanje, multimedijalni sistemi, digitalno učenje, tekstilna sito štampa.*

1. INTRODUCTION

The education of future textile and graphic engineers is increasingly influenced by the digital transformation of teaching and learning environments [1-4]. Contemporary students are exposed to large volumes of information through various digital channels, which has significantly changed their expectations regarding educational content and methods of knowledge acquisition. As a consequence, traditional lecture-based approaches are often insufficient for explaining technological processes that involve multiple stages, interactions between materials and equipment, and dynamic production parameters [2, 4].
Within engineering education, particular challenges arise when teaching printing technologies. Printing processes are characterized by the simultaneous interaction of mechanical, chemical, physical and visual phenomena, making them difficult to present through static text and images alone [5]. For this reason, educational approaches that combine visual, auditory and interactive elements have attracted considerable attention in recent years [6, 7].
The theoretical foundation of such approaches can be found in the Cognitive Theory of Multimedia Learning, which assumes that meaningful learning occurs when learners actively integrate verbal and visual information into coherent mental representations [6, 8]. Research has demonstrated that appropriately designed multimedia materials can improve understanding, increase learner engagement and reduce cognitive overload, especially when complex technical concepts are involved [6-7].
Screen printing represents one of the most important conventional printing techniques used in textile production. Despite the rapid development of digital printing technologies, screen printing remains widely applied because of its versatility, durability, colour intensity and suitability for large production runs [5, 10]. The process includes a series of interconnected stages, including artwork preparation, screen production, stencil creation, ink preparation,

printing and curing. Understanding the relationships between these stages requires students to visualize process sequences, equipment operation and material behaviour, which often presents difficulties in traditional classroom instruction [10].

Recent advances in digital educational technologies have created opportunities to enhance the teaching of screen printing through multimedia-supported learning environments [1, 3, 4].

Video-based instruction, animated process demonstrations, narrated presentations and interactive learning materials allow students to observe technological procedures repeatedly and at their own pace [7-9].

This paper presents a multimedia-based approach to screen printing education developed according to established multimedia learning principles. The proposed methodology combines structured instructional materials, visual demonstrations and narrated educational content into a unified learning resource. The objective is not only to improve the presentation of screen-printing technology but also to explore how multimedia-supported instruction can contribute to more effective learning outcomes in textile and graphic engineering education.

2. THEORETICAL BACKGROUND OF MULTIMEDIA LEARNING

Multimedia learning represents one of the most influential approaches in contemporary educational practice [6, 8]. According to the Cognitive Theory of Multimedia Learning, learners achieve deeper understanding when information is presented through a combination of verbal and visual representations rather than through text alone [6]. Educational materials designed according to multimedia principles support active cognitive processing, facilitate knowledge construction and improve long-term retention [8, 9].

Several multimedia design principles have been identified as particularly important for technical and engineering education. These include the multimedia principle, coherence principle, signaling principle, spatial and temporal contiguity principles, modality principle and segmentation principle [6, 8].

The application of these principles is especially relevant when teaching technological processes that involve multiple interconnected stages and dynamic production operations [7, 9].

Screen printing education represents a suitable field for applying multimedia learning because students must simultaneously understand equipment configuration, stencil preparation, ink transfer mechanisms and substrate interaction [10]. These concepts are often difficult to explain through static textual descriptions alone, making multimedia-supported instruction particularly valuable [7, 8].

3. SCREEN PRINTING AS A COMPLEX EDUCATIONAL TOPIC

Screen printing remains one of the most widely used printing technologies in textile production and industrial decoration applications [5, 10]. Despite the growth of digital

printing technologies, screen printing continues to be important because of its versatility, durability and suitability for a wide range of textile applications.

The educational process involves teaching numerous theoretical and practical concepts, including screen preparation, stencil production, image transfer, ink selection, printing parameters and curing procedures. Students are required to understand not only individual process stages but also their interactions and influence on final print quality [10].

Visual demonstrations and multimedia-supported explanations can significantly contribute to improved understanding of screen printing technology and facilitate the acquisition of practical knowledge.

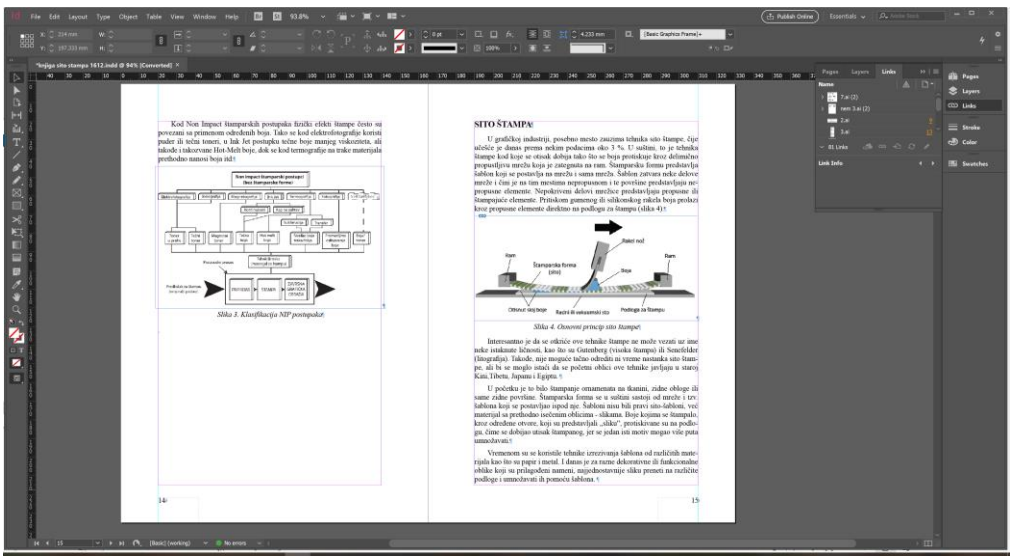

Figure 1: Initial instructional material prepared for screen-printing education

4. DEVELOPMENT OF MULTIMEDIA EDUCATIONAL MATERIAL FOR SCREEN PRINTING

The development of the educational material followed a structured workflow based on multimedia learning principles [6-9].

Table 1: Application of multimedia learning principles in the development of the screen-printing lesson

Multimedia learning principle	Application in the developed lesson
Multimedia principle	Combination of narration, images and diagrams
Coherence principle	Removal of unnecessary text and decorative elements from slides
Signaling principle	Emphasis on key concepts and process stages
Spatial contiguity principle	Positioning of the avatar close to visual content
Modality principle	Use of spoken narration instead of extensive on-screen text
Segmentation principle	Division of the lesson into smaller instructional units

Table 1 summarizes the multimedia learning principles incorporated into the development of the educational material. The practical implementation of these principles throughout the lesson creation process is illustrated in Figures 1–9.
The instructional material was initially prepared in digital format containing textual explanations and graphical representations of screen-printing processes.
The prepared material was then transformed into a PowerPoint presentation. Detailed explanations were placed within speaker notes, while slides contained only essential information and supporting visuals.
This approach reduces unnecessary cognitive load and supports learner attention in accordance with multimedia learning principles [6, 8].

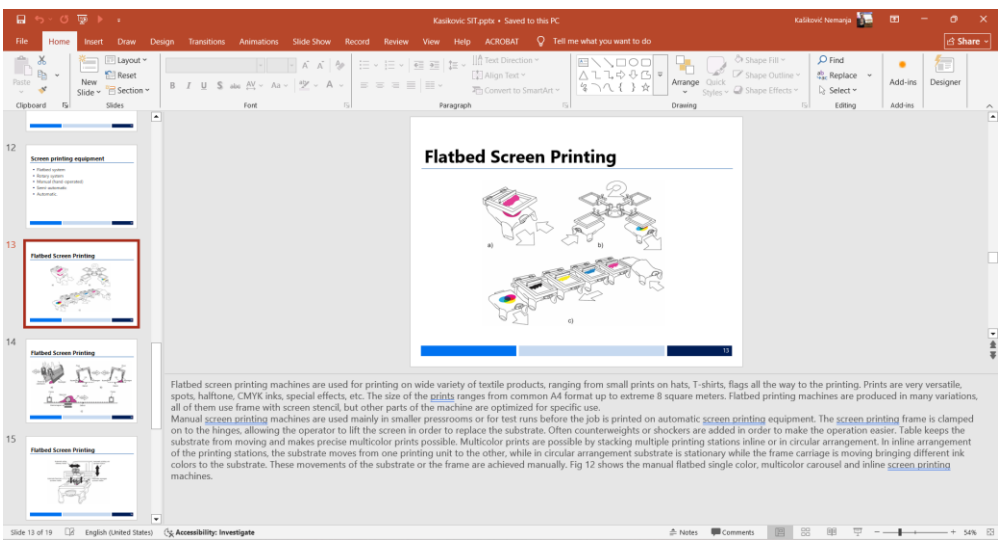

Figure 2: Transformation of instructional content into a PowerPoint presentation following the coherence principle

Following the preparation of the presentation, the Studio D-ID platform was used for multimedia lesson creation.

A new project was created, and the lesson template selected according to educational requirements.

A personal avatar representing the lecturer was selected and positioned in the lower-right corner of the presentation frame.

This placement was chosen to maintain spatial contiguity between narration and visual content while avoiding obstruction of important graphical elements [6, 8].

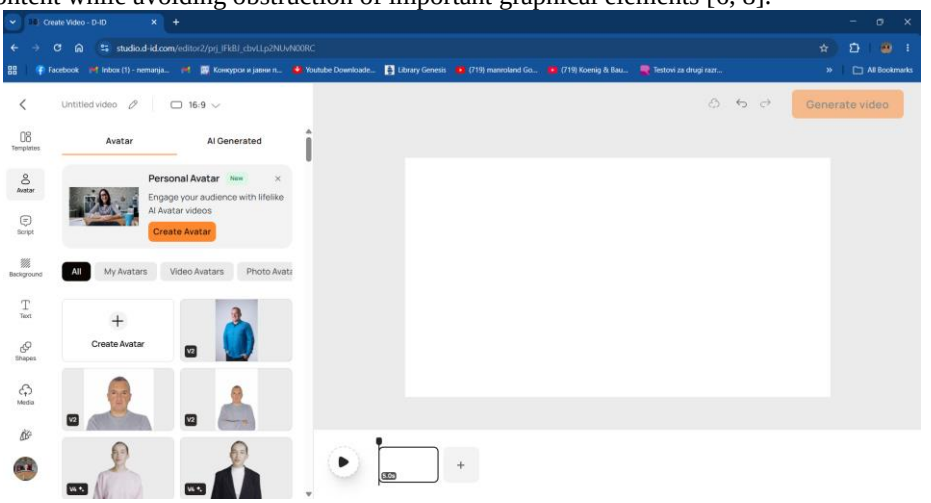

Figure 3: Selection of a personal avatar for multimedia lesson creation within Studio D-ID

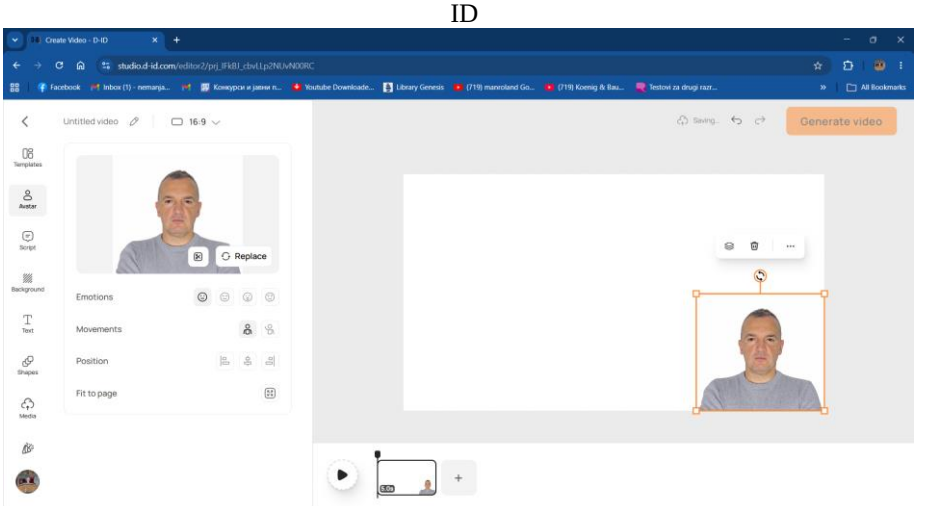

Figure 4: Implementation of the spatial contiguity principle through avatar placement

Relevant visual materials illustrating screen-printing processes were then selected and integrated into the lesson. The platform enables the incorporation of images, presentations and additional multimedia resources into individual learning segments.

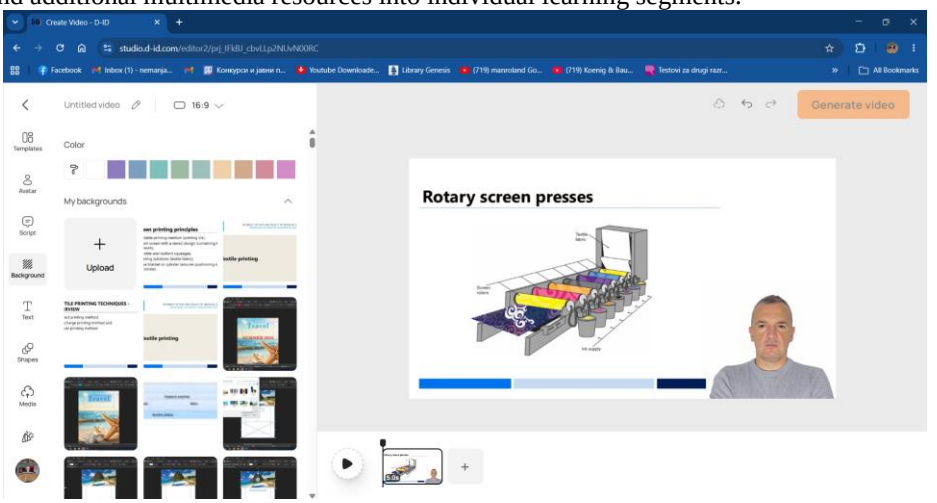

Figure 5: Integration of visual materials into the multimedia lesson

All verbal explanations were entered into the script section of the platform. The system allows the selection of narration language, voice characteristics and speech rate. These options provide flexibility for adapting instructional materials to different educational contexts and learner needs.

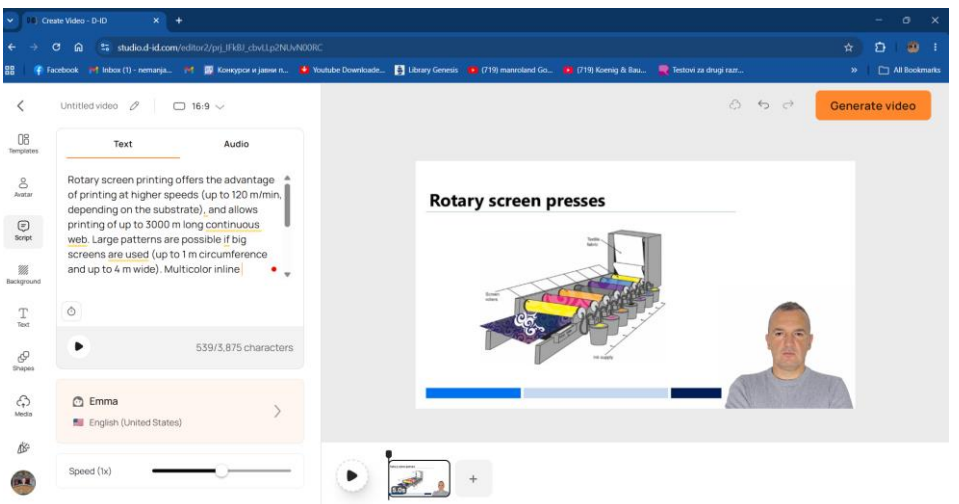

Figure 6: Script preparation for narrated multimedia instruction

After script preparation, an appropriate voice profile and speech configuration were selected. Such customization contributes to improved learner engagement and presentation clarity.

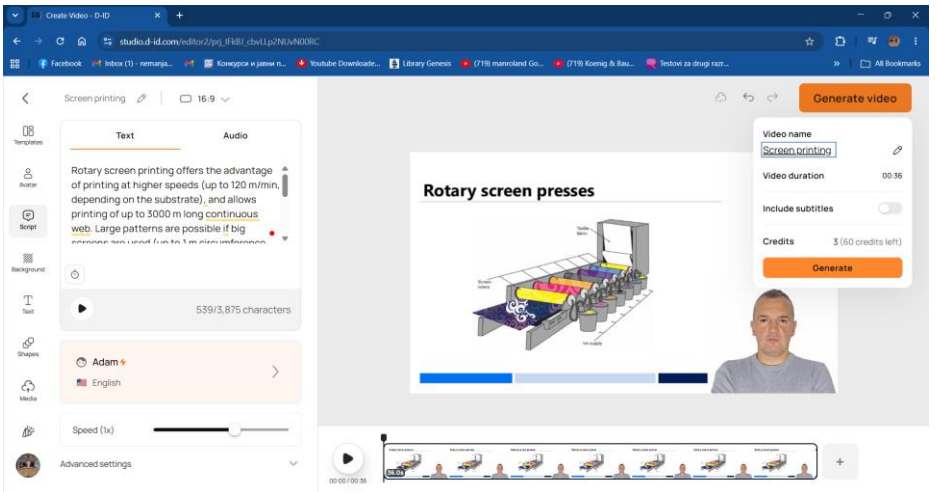

Figure 7: Application of the modality principle through narrated instruction

After completing the preparation process, the multimedia lesson was generated automatically by the platform. The resulting educational material was then downloaded and prepared for classroom, online and blended-learning applications.

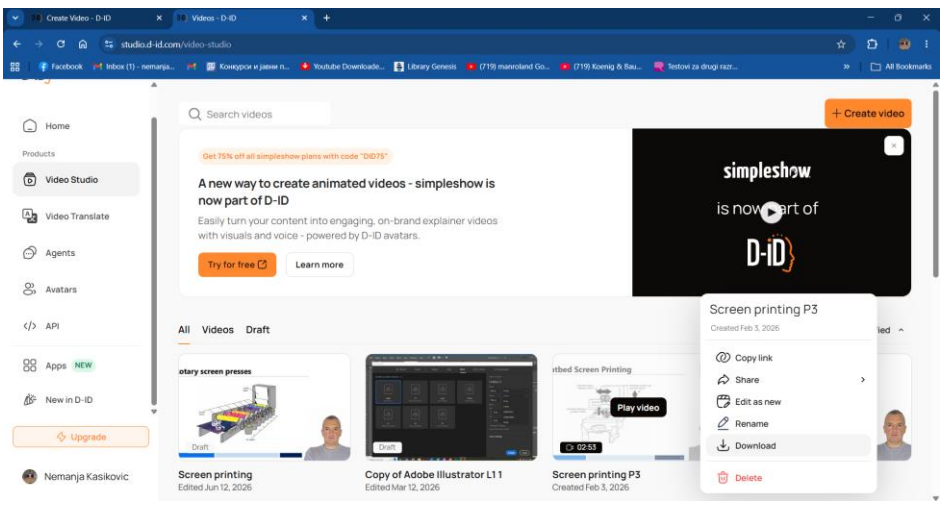

Figure 8: Generation and export of the final multimedia educational material

5. CASE STUDY: MULTIMEDIA LESSON ON SCREEN PRINTING

The developed multimedia lesson presents the fundamentals of screen-printing technology, including flatbed and rotary screen-printing systems, stencil formation, ink transfer mechanisms and process characteristics. The lesson combines narration, visual demonstrations and animated explanations into a single educational resource designed according to multimedia learning principles.
The complete educational video developed within this study is publicly available and can be accessed through the following link:
https://www.youtube.com/watch?v=X3X4TTuCLuM&t=35s
The video enables students to observe process stages repeatedly, supporting self-paced learning and reinforcing theoretical concepts through synchronized visual and verbal explanations.

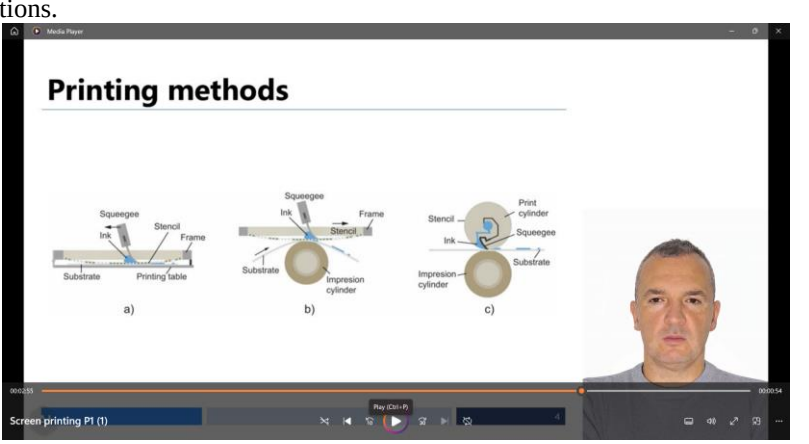

Figure 9: Final multimedia lesson on screen-printing technology available through an online video platform

The developed multimedia lesson was designed according to several established multimedia learning principles. Table 2 summarizes the development workflow of the multimedia lesson and links each phase of the process with the corresponding figure presented in this paper.

Table 2: Workflow for multimedia lesson development

Phase	Activity	Related figure
Content preparation	Preparation of instructional material	Figure 1
Presentation design	Conversion into PowerPoint format	Figure 2
Avatar creation	Selection and positioning of avatar	Figures 3-4
Multimedia integration	Uploading visual material	Figure 5
Narration preparation	Script writing and voice selection	Figures 6-7
Video generation	Exporting the final lesson	Figure 8
Final educational resource	Published multimedia lesson	Figure 9

6. DISCUSSION

The proposed methodology demonstrates how multimedia learning principles can be incorporated into screen-printing education. By combining structured instructional content, visual demonstrations, narration and AI-assisted presentation technologies, educational material becomes more accessible and engaging for students.
The methodology offers several advantages, including flexibility of delivery, support for online and blended learning, content reusability and increased student engagement. Furthermore, the approach can be adapted to other textile and printing technologies where visualization of complex processes is required.
The use of AI-supported multimedia tools should not be considered a replacement for traditional teaching methods but rather a complementary educational resource that enhances knowledge transfer and improves accessibility to instructional content.
Despite the advantages, the development of multimedia educational materials requires considerable preparation time, technical competencies and access to specialized software platforms. Furthermore, the effectiveness of such materials depends on instructional design quality rather than technology itself.

7. CONCLUSION

This paper presented a multimedia-based methodology for teaching screen-printing technology. The proposed approach combines instructional design principles, multimedia learning theory and AI-supported content-generation tools to create educational materials suitable for contemporary engineering education.
The presented case study demonstrates the practical workflow for developing multimedia lessons and highlights the potential benefits of integrating visual, verbal and interactive educational resources into screen-printing instruction.
Future research will focus on empirical evaluation of learning outcomes through experimental studies involving student groups, questionnaires and statistical analysis of educational effectiveness. Such investigations will provide objective evidence regarding the influence of multimedia-supported instruction on learning outcomes in textile and graphic engineering education.
The proposed methodology may serve as a framework for developing multimedia lessons not only in screen printing but also in other textile manufacturing and graphic engineering courses.

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THE COMPARISON OF VARIOUS POLYMER BASED NANOFIBERS COATED RECYCLED NONWOVENS ON THE SOUND ABSORPTION PROPERTIES

Scientific paper
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ABSTRACT: *In recent years, the development of innovative and eco-friendly acoustic materials is increasingly important for solving noise problems in industrial and architectural areas.This study aims to determine the optimum polymer type for fabricating high performance sound absorbing nanofibers, which are to be coated onto recycled PET-based nonwoven surfaces via the electrospinning method. For this purpose, different polymer/solvent solutions such as polyvinyl alcohol (PVA), polyacrylonitrile (PAN), cellulose acetate (CA), and polyurethane (PU) were prepared. Subsequently, the viscosity, surface tension, and electrical conductivity characteristics of these solutions were investigated. In addition, the morphological structures of the nanofibers were analyzed using Scanning Electron Microscopy (SEM), and their average fiber diameters and uniformity coefficients were determined. Additionally, the air permeability and sound absorption (NRC) properties of 500 g/m² nonwovens coated with different polymer-based nanofibers were compared to an uncoated sample using the impedance tube method. It was found that the nanofiber coating significantly enhanced sound absorption by reducing air permeability from 4502 l/m²/s to 352.8 l/m²/s. Sound absorption tests were revealed that while the NRC value of the uncoated fabric was 0.105, the highest performances were achieved with PVA (0.212) and PAN (0.207) based nanofibers. PVA was selected as the optimum polymer due to its balanced sound absorption across a wide frequency range, bead free and homogenous fiber morphology, and environmental sustainability advantages provided by using DI water as a solvent.*

Keywords: *Electrospinning, Nanofiber, Recycle PET, Nonwoven, Sound Absorption.*

POREĐENJE UTICAJA RECIKLIRANOG NETKANOG TEKSTILA PRESVUČENOG NANOVLAKNIMA NA BAZI RAZLIČITIH POLIMERA NA SVOJSTVA APSORPCIJE ZVUKA

APSTRAKT: *U poslednjih nekoliko godina, razvoj inovativnih i ekološki prihvatljivih akustičkih materijala postaje sve značajniji za rešavanje problema buke u industrijskim i stambenim objektima. Ova studija ima za cilj određivanje optimalnog tipa polimera za izradu nanovlakana visokih performansi za apsorpciju zvuka, koja se nanose na površine netkanog tekstila na bazi recikliranog PET-a metodom elektroispredanja (elektrostatičkog ispredanja). U tu svrhu pripremljeni su različiti rastvori polimera i rastvarača, kao što su polivinil-alkohol (PVA), poliakrilonitril (PAN), celuloza-acetat (CA) i poliuretan (PU). Nakon toga, ispitane su karakteristike ovih rastvora poput viskoznosti, površinskog napona i električne provodljivosti. Pored toga, morfološka struktura nanovlakana analizirana je pomoću skenirajuće elektronske mikroskopije (SEM), te su određeni njihovi prosečni prečnici vlakana i koeficijenti uniformnosti. Takođe, svojstva propustljivosti vazduha i apsorpcije zvuka (NRC – koeficijent redukcije buke) netkanog tekstila površinske mase 500 g/m² presvučenog nanovlaknima na bazi različitih polimera upoređena su sa neprevučenim uzorkom pomoću metode impedansne cevi. Utvrđeno je da nanos nanovlakana značajno poboljšava apsorpciju zvuka smanjenjem propustljivosti vazduha sa 4502 l/m²/s na 352,8 l/m²/s. Testovi apsorpcije zvuka pokazali su da je, dok je NRC vrednost neprevučenog tekstila iznosila 0,105, najviša efikasnost postignuta sa nanovlaknima na bazi PVA (0,212) i PAN-a (0,207). PVA je izabran kao optimalan polimer zbog svoje uravnotežene apsorpcije zvuka u širokom opsegu frekvencija, homogene morfologije vlakana bez pojave struktura nalik kapljicama (kuglicama), kao i zbog ekološke održivosti koju pruža korišćenje dejonizovane (DI) vode kao rastvarača.*

Ključne reči: *Elektroispredanje, Nanovlakno, Reciklirani PET, Netkani tekstil, Apsorpcija zvuka.*

1. INTRODUCTION

Sound is an essential part of life; however, noise is an inherent consequence of contemporary urbanization that adversely affects human health. Research shows that excessive noise is the primary cause of behavioral and psychological disorders, decreased efficiency, hearing loss, and various problems, especially in unplanned urbanization areas. In this context, textile materials offer a highly effective solution for noise reduction and the attenuation of acoustic disturbances. In this study, recycled nonwoven fabric are used; these are preferred high-performance materials due to their porosity, reusability, sustainability, and elasticity [1].

Nanofibers show high-performance features due to their small fiber diameter (nm), open pores, high porosity, and large specific surface area (m²/g).

As known from the literature that nanofiber materials dramatically increase the airflow resistance significantly improving sound absorption efficiency particularly at low-to-medium frequencies [2]. The performance of the nanofiber coating is significantly dependent on the specific properties of the polymer used. Therefore, polyvinyl alcohol (PVA), polyacrylonitrile (PAN), cellulose acetate (CA), and polyurethane (PU) polymers

were used to compare optimum sound balance, polymer selection, and fiber homogeneity in this study.

2. MATERIALS AND METHODS

2.1. Materials

In this study, PVA (Aldrich Chemistry, Mw 85,000- 124,000), PAN (Aldrich Chemistry, Mw 150,000), PU (Elastollan 1185 A10, BASF Firm), CA (Aldrich Chemistry, Mw 30,000) were used as polymers; dimethylformamide (DMF) (Fluka Chemika), dimethylacetamide (DMAc) (Fluka Chemika), Deionized (DI) water and acetone (ACE) (Isolab Chemicals) were used as solvents to produce nanofibers. Recycled PET-based nonwoven fabric with a surface density of 500 g/m² was employed as the substrate for the nanofiber coating (UC500).

Table 1: Sample coding according to polymer types (Base Material: 500 g/m² R-PET Nonwoven fabric)

Polymer	Base Sample	Coated Sample Code
PVA	UC500	PVA500
PAN	UC500	PAN500
PU	UC500	PU500
CA	UC500	CA500

2.2. Methods

Polymer solutions of PVA (10 wt%), PAN (7 wt%), PU (14 wt%), and CA (16 wt%) in a DMAc/acetone mixture (1:2, wt/wt) at room temperature were prepared by stirring for 24 hours. The PU and PAN solutions were stirred under heating.

The viscosity, surface tension and electrical conductivity values of the solutions were figured out by a viscometer (Lamy Rheology, B-One Touch Screen), surface tension meter (Biolin Scientific 703), and an electrical conductivity meter (Selecta CD 2005), respectively.

An electrospinning setup consisted of a single needle with a 0.8 mm diameter cut tip, an aluminium collector, a syringe pump, and a power supply (Matsusada, 40 kV). Afterwards, the textile materials were cut into 15x15 cm pieces, and the collector plate was prepared for the electrospinning process. Then, nanofibers were electrospun from the prepared polymer solutions for an equal duration of 30 min onto the base textile materials. The electrospinning process parameters are detailed in Table 2.

Table 2: Process parameters of electrospinning

Polymer / Solvent	Voltage (kV)	Distance between electrodes (cm)	Feed rate (mL/h)	Humidity (%)	Temperature (°C)	Needle Diameter (mm)
PAN / DMF	21.2	19.5	0.65	32	22.8	19.5
PU / DMF	19.9	20	0.9	32	22.2	19.5
PVA/DW	21.7	20	0.5	33	23	19.5
CA/DMAc:Acetone	22	19.5	0.2	32	22.1	19.5

Scanning electron microscope (SEM) (FEI Quanta 250 FEG) and image analysis software (Image J programme) were taken for the fiber morphological analysis and measurement average fiber diameter respectively. To calculate the mean diameter, 100 nanofibers were selected randomly from the obtained SEM images. The nanofibers diameter uniformity was calculated via using the formulas given below 1 and 2 [3]. Then, histogram graphics were originated as a result of this calculation with the help of Microsoft SPSS version 27.

$$A_n = \frac{\Sigma n_i d_i}{\Sigma n_i} \text{ (Number average)} \quad (1)$$

$$A_w = \frac{\sum n_i d_i^2}{\sum n_i d_i} \text{ (Weight average)} \quad (2)$$

ni=fiber number *di=fiber diameter*

Then, Sound Absorption Coefficient (SAC) and Noise Reduction Coefficient (NRC) values were carried on impedance tube method with ISO 10534-2 standard. Lastly, air permeability was conducted for coated and uncoated textile materials according to the EN-ISO 9237 standard.

3. RESULT AND DISCUSSION

3.1. Polymer Solution Characterization

Polymer solution properties were measured in terms of understanding their effect on fiber spinning performance. In this study, the viscosity, surface tension and electrical conductivity results of the solutions were first determined. According to the obtained results, these values for the prepared polymer solutions are presented in Table 3.

Table 3: Solution Properties of PAN, PU, PVA and CA

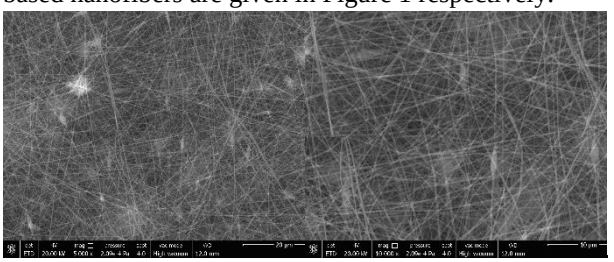
Sample	Viscosity (mPa.s)	Surface Tension (mN/m)	Electrical Conductivity (µS/cm)
8 wt% PAN / DMF	406,2	35,01	55,5
14 wt% PU / DMF	1850	44,50	1,62
10 wt% PVA / DW	977,8	31,76	728
16 wt% CA/DMAC:AC	625,7	15,60	6,29

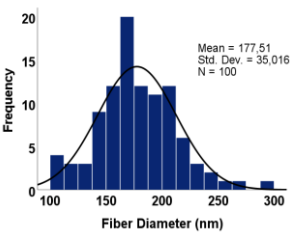
Acoording to the table 3, PVA solution exhibited a highest electrical conductivity (728 µS/cm) and high viscosity (977.8 mPa·s) due to the high polarity and inherent properties of the deionized water solvent. Since the electrical conductivity of polymer solutions is directly related to the number of ions present, the lower conductivity values of the other solutions are attributed to the organic nature of their solvents [4]. Conversely, the PU solution demonstrated the highest viscosity (1850 mPa·s) and the highest surface tension (44.50 mN/m).

Upon analysis of surface tension values, while PU and PAN solutions had higher values, the CA solution stood out with the lowest surface tension (15,60 mN/m). These combined physical properties are expected to directly influence the average fiber diameters and structural homogeneity observed in the SEM analysis.

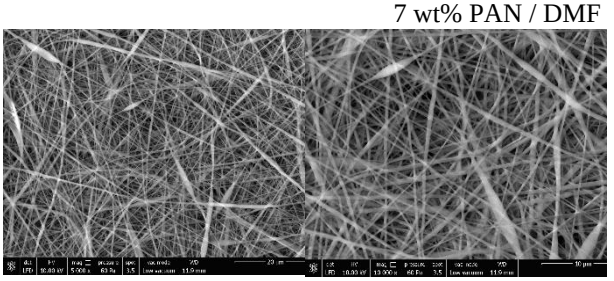
3.2. Fiber Morphology Results

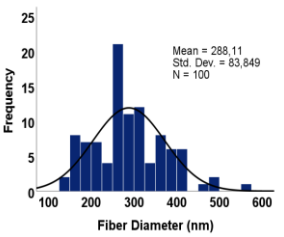
SEM images (5.000x and 10.000x) and fiber diameter histograms of PAN, PU, PVA, CA based nanofibers are given in Figure 1 respectively.



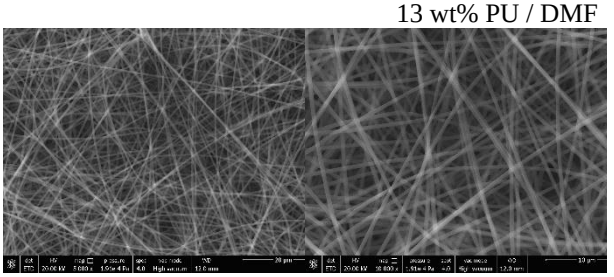


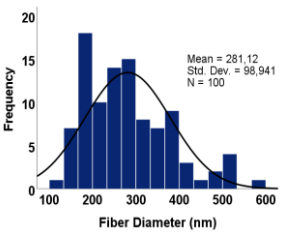
7 wt% PAN / DMF



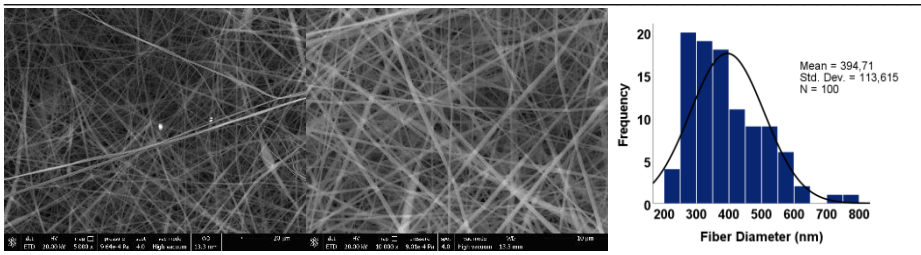


13 wt% PU / DMF





10 wt% PVA / DI water



16 wt% CA / Dmac:Ace

Figure 1: SEM images (5000x- 10000x) and histograms of PAN, PU, PVA and CA nanofibers produced

When SEM images were analyzed, it was determined that the PAN and PU nanofibers exhibited bead formation**,** at the concentrations initially specified. However, the PU and PAN solution concentrations were increased to 14 wt% and 8 wt%, respectively, to reach the ideal viscosity, thus bead-free and stable fiber networks were successfully obtained. Conversely, in the 10 wt% PVA/deionized water solution, the high polarity of water resulted in high electrical conductivity (728 µS/cm), while in the 16 wt% CA/DMAc-acetone solution, the optimal combination of process parameters allowed for the direct formation of homogeneous, continuous, and bead-free nanofiber in the initial stage.

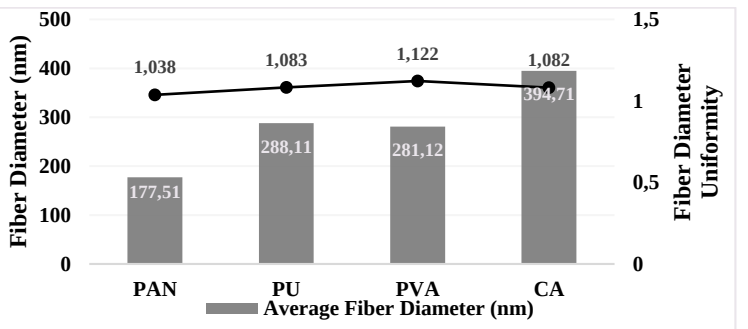


Figure 2: Evaluation of mean fiber diameters and fiber diameter uniformity coefficients (Aw/An) of different electrospun nanofibers.

According to the results, the 8 wt% PAN nanofibers exhibited the thinnest average fiber diameter of 177.51 nm and a uniformity coefficient of 1.038, demonstrating the most uniform distribution in the study. The 14 wt% PU nanofibers presented a balanced distribution with a mean fiber diameter of 288.11 nm and a uniformity coefficient of 1.047. On the other hand, the 10 wt% PVA nanofibers reached a mean fiber diameter of 281.12 nm, but exhibited the highest uniformity coefficient of 1.122, confirming the most irregular fiber diameter distribution. Lastly, the 16 wt% CA nanofibers produced the thickest structures in this study, with average fiber diameter of 394.71 nm and a diameter uniformity coefficient of 1.083. In this study, the sound absorption performance of the produced

nanofiber-coated textile materials was determined using a two-microphone impedance tube with the ISO 10534-2 standards (Figure 3).

Figure 3: Impedance tube used in the study

The sound absorption coefficients (SAC) of the uncoated nonwoven fabric (UC500) and the nanofiber-coated samples (PVA500, PAN 500, CA500, and PU500) measured in the 1/3 octave frequency bands are illustrated in Figure 4.

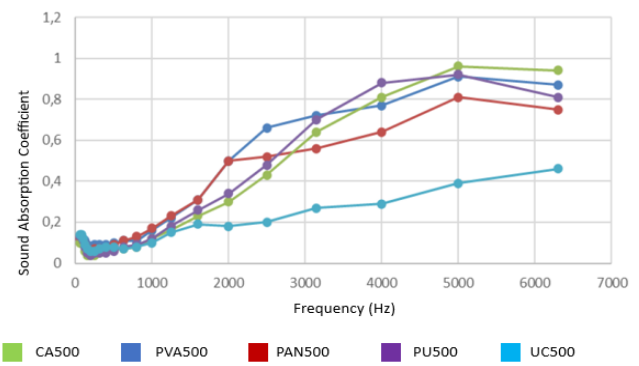


Figure 4: Presents the sound absorption coefficient values of each textile sample before and after coating.

It is seen that nanofiber-coated samples show much better sound absorption than the uncoated UC500 sample, especially between 1000 and 5000 Hz. This frequency range is very important because it represents the most common noises we hear in daily life, such as human voices, phone ringtones, TV sounds, and a baby crying [5]. While the plain nonwoven fabric (UC500) stayed quite low with a maximum value of 0.46, the nanofiber coatings clearly boosted the performance. Specifically, PVA500 and PAN500 reached the highest points with values of 0.92 and 0.91 at 5000 Hz. These results prove that adding a

thin layer of electrospun nanofibers is a highly effective way to block and reduce disturbing everyday noises.

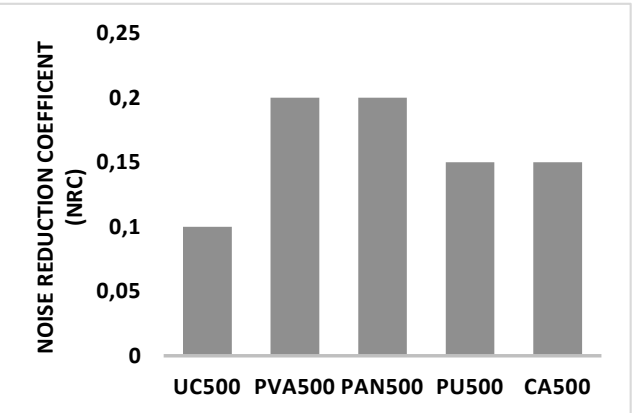


Figure 5: Noise Reduction Coefficent of all samples

According to the graph, NRC value is higher for all nanofiber-coated samples compared to the uncoated UC500 sample. These results clearly prove that adding a nanofiber layer successfully improves the general noise reduction capability of the fabrics. To better understand these sound absorption results, the physical properties of our samples, such as air permeability and thickness are given and compared in Table 4.

Table 4: Air permeability and Cross-section thickness (for total fabric thicknesses) of all samples

Sample Codes	Air Permeability (l/m²/s)	Cross-section thickness (mm)
UC500	4502	1.684
PVA500	352.8	1.705
PAN500	594.6	1.701
PU500	883.8	1.694
CA500	1974	1.688

According to the results, there is a clear relationship between the fabric thickness and air permeability after the electrospinning coating. The uncoated nonwoven sample (UC500) has the highest air permeability value with 4502 l/m²/s and the lowest thickness of 1.684 mm. When it was analyzed nanofiber-coated samples, their air permeability values are much lower compared to the uncoated sample.

4. CONCLUSION

In conclusion, based on all the experimental findings, PVA was selected as the most suitable polymer for high-performance sound absorption applications. PVA500 provides a well-balanced and steady increase in the sound absorption coefficient from low to high frequencies. This polymer offers a highly effective acoustic solution especially within the 2500–5000 Hz frequency band, which directly represents common daily environmental noises such as restaurant, cafe, and meeting room sounds.
In addition to its sound absorption success, the material properties of PVA play a critical role in this selection. Thanks to its bead-free and highly homogeneous fiber structure, it ensures a stable surface production and reliable sound absorption performance. Furthermore, PVA stands out as an eco-friendly polymer. Since water is used as its solvent, it was strongly preferred by prioritizing environmental sustainability and green chemistry.

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THE TEXTILE INDUSTRY OF ZEMUN IN THE INTERWAR PERIOD AND ITS SIGNIFICANCE FOR THE LATER DEVELOPMENT OF THE TEXTILE INDUSTRY

Scientific paper
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ABSTRACT: *This paper examines the development of the textile industry in Zemun, Serbia, with a primary focus on the interwar period (1919–1941), through case studies on the establishment and operation of several factories and workshops producing various types of knitwear, as well as the significance this industry had for the later development of the textile sector.*

Keywords: *textile industry, interwar period, Zemun, Serbia, development.*

TEKSTILNA INDUSTRIJA ZEMUNA U MEĐURATNOM PERIODU I NJEN ZNAČAJ ZA DALJI RAZVOJ TEKSTILNE INDUSTRIJE

APSTRAKT: *Ovaj rad razmatra razvoj tekstilne industrije u Zemunu, Srbija, sa posebnim osvrtom na međuratni period (1919–1941), kroz studije slučaja o osnivanju i radu nekoliko fabrika i radionica za proizvodnju različitih vrsta pletiva, kao i o značaju koji je ova industrija imala za kasniji razvoj tekstilnog sektora.*

Ključne reči: *tekstilna industrija, međuratni period, Zemun, Srbija, razvoj.*

1. INTRODUCTION

The textile industry in Zemun (present – day Serbia) before 1914 did not exist in the form of large modern factories but was instead exclusively based on artisanal and small-scale manufacturing production.
Key characteristics of the period before 1914: Dominance of craftsmanship: Textile production was carried out in small household workshops, weaving shops, and tailoring

guilds. These enterprises barely exceeded the scale of local craft production. Family tradition: The economic development of Zemun accelerated with the construction of the Budapest–Subotica–Zemun railway in 1883 and the introduction of electric street lighting in 1901. These developments created the technical conditions for subsequent industrialization. Market orientation: Zemun functioned primarily as a commercial center. Textile products were more often imported and traded than manufactured locally on an industrial scale.

Zemun is distinguished by the fact that, during the interwar period, a large number of factories of various industrial profiles were established, with the textile industry accounting for the largest share. Between the two World Wars, industry in the Municipality of Zemun experienced significant expansion.

Following the First World War, only about forty small enterprises existed in Zemun, most of which scarcely exceeded the level of artisanal production. Various incentives granted by the municipal authorities to industrial entrepreneurs, together with the introduction of protective tariffs in 1925, [1, 2] made a substantial contribution to industrial development. As existing craft workshops evolved into industrial enterprises and numerous new factories were established, the textile industry became one of the most highly developed industrial sectors in Zemun during the interwar period. Several factors contributed to this development, ranging from the implementation of protective tariffs to the relatively higher wages earned by workers employed in the textile industry.

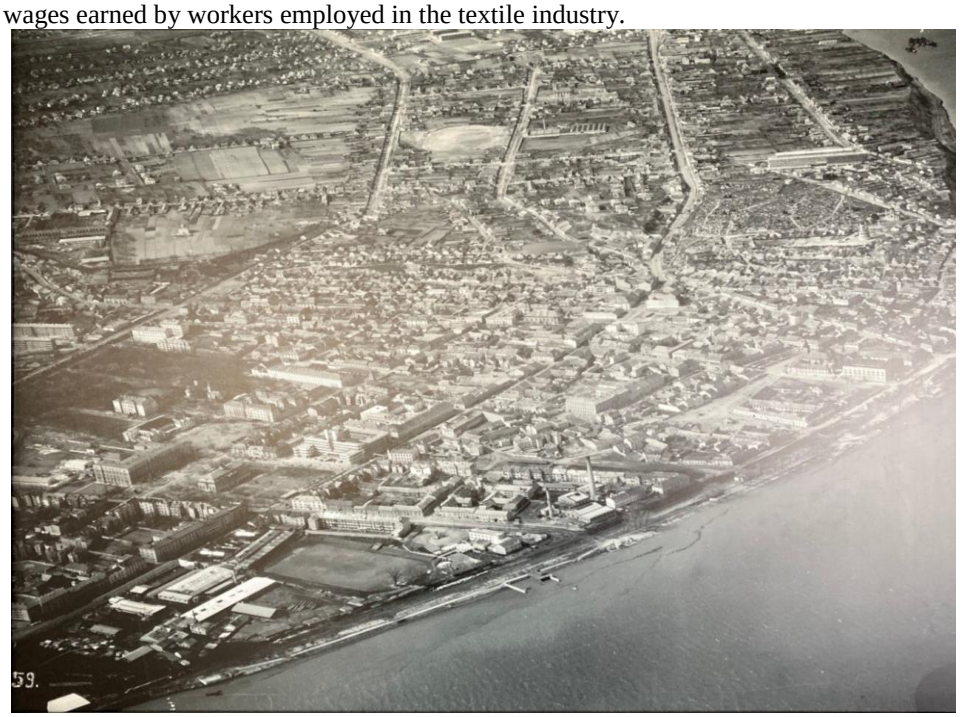

Figure 1. Aerial panorama of Zemun, 1930s. From the private collection of Miloš Jurišić

The most important factories that shaped the development of the textile industry in Zemun between the two World Wars included: the Woolen Cloth Factory (*Tvornica vunenih tkanina*) of Živojin Vukojičić and partners; the Plush and Velour Factory (*Tvornica klimera i pliša*) of Svetozar Mitić; the Merino Woolen Cloth Factory (*Merino*) owned by Adolf Reiss; Zemun Textile Industry Joint-Stock Company (*Zemunska tekstilna industrija a.d.*) founded by Aleksandar Dingarac, Aleksa Stojanović, and Dobrivoje Goločevac; Franz Devald's Stocking Factory; Johann Boros's Knitting Workshop (*Štrikeraj*) in Pavlova Street (today Rada Končara Street); the Krango Brothers Factory; Milan Nikolić's Military Clothing and Uniform Factory located on Veliki Trg (Great Square); Sava Knitwear (*Trikotaža Sava*) owned by Ljubomir J. Stefanović & Co.; Milorad St. Janković's Textile Industry on Železnički Put (Railway Road); Javor Mechanical Weaving Mill owned by Vuković and Stojanović; Tibet Textile Industry owned by Viktor Berger; Plaros Weaving Mill owned by Popović and Mihajović; Tekstilind Knitwear Factory owned by Rudolf Klopfer; Yugoslav Textile Industry and Trade Joint-Stock Company; Branko Tokin's Textile Industry; Stela Textile Industry Joint-Stock Company; the First Yugoslav Silk Weaving Company (*Prva jugoslovenska tkaonica svilene robe d.d.*); Dejan Frušić's Silk Fabric Factory; the Avala Mechanical Weaving Mill (*Mehanička tkačnica Avala*) owned by Radoslav Bešević and Dušan Živković; Jadran Textile Industry owned by David M. Levi; Danubius Textile Industry owned by Mosko Nahmijas; the Devald Brothers' factories; as well as several other smaller textile enterprises. [3, 4, 5]

2. BRIEF OVERVIEW OF SELECTED TEXTILE FACTORIES IN ZEMUN DURING THE INTERWAR PERIOD

2.1 Živojin Vukojičić & Sons Textile Industry Joint-Stock Company

The factory was primarily engaged in the production of woolen fabrics and ranked among the most important textile enterprises in the area of present-day Belgrade during the interwar period. It was officially registered in 1926 in Zemun at14 Factory Street (Tvornička Street) The owner was Živojin Vukojičić, while the factory was managed by his sons, Budislav and Dragomir Vukojičić. Although the factory was destroyed by fire in 1928, production resumed in 1929.

By 1934, the enterprise had developed into a fully integrated textile mill, comprising a spinning mill, weaving mill, finishing department, and dyeing plant. The factory operated throughout the year in two shifts and employed up to 150 workers. Its product range included high-quality woolen fabrics for men's and women's clothing, military blankets, and broadcloth (*čoja*). Part of the yarn, particularly that intended for the production of finer fabrics, was imported, while the remainder was spun on-site.

In addition to the domestic workforce, the factory employed skilled workers from abroad, including immigrants from Russia, Poland, Czechoslovakia, and Italy. As production expanded, operations were extended to three shifts, and the workforce increased to as many as 300 employees.

Following the death of Živojin Vukojičić, ownership of the factory passed to his sons, Budislav, Vladislav, and Dragomir. In 1939, the company was reorganized as a joint-stock

company, with the majority of shares, valued at 15,000,000 dinars, remaining in the possession of the Vukojičić brothers [3, 4, 5].

Figure 2: Factory Plan. Archives of Yugoslavia, 65-572-1292.

2.2 The Devald Brothers Textile Enterprise: “Drina” Knitting Factory Owned by Anton Devald and “Dunav” Knitting Factory Owned by Nikola Devald

The Devald family was a Zemun-based family of German origin with a long tradition in textile manufacturing. Adam Devald owned a textile factory in Zemun, and his sons, Anton and Nikola Devald, continued the family business in textile production. In 1918, they established a textile enterprise under the name “Devald Brothers” (*Braća Devald*).

The company headquarters were located at 57 Kraljice Marije Street. The location of the enterprise was favorable, situated approximately 1.5 kilometers from the railway station and 2.5 kilometers from the river port. However, their joint business operation lasted only briefly. In 1919, the brothers separated their business activities, and Anton Devald founded an enterprise that operated under the name “Drina” Knitting Factory.

The factory initially focused on stocking production, but its manufacturing program was later expanded to include a wider range of knitted textile products. Devald invested approximately 300,000 dinars in factory buildings, while investments in machinery and equipment were considerably higher, amounting to around 800,000 dinars. The factory complex included spinning departments, knitting workshops, a drying facility, a building with a steam boiler, a finished goods warehouse, a retail store, offices, and a garage.

The largest volume of production took place during the main season, which lasted from August to March, while operations outside the season were significantly reduced. Under normal operating conditions, the factory employed up to 50 workers, while continuous production required a workforce of approximately 120 employees.
The factory's main products included waistcoats, pullovers, sweaters, and knitted footwear. Secondary products included children's gloves, scarves, wristbands, and gloves.
Following the separation from his brother, Nikola Devald established his own textile production enterprise. He made substantial investments in machinery and equipment; however, combined with the economic crisis and difficult business conditions at the end of the 1920s and the beginning of the 1930s, these investments brought the company close to bankruptcy. Devald succeeded in reaching a financial settlement with creditors and extended the operation of his factory, which he officially registered under the name "Dunav" Knitting Factory (*Trikotaža "Dunav"*) in 1932.
The company headquarters were located at 29 Kraljice Marije Street. The factory site covered an area of 15 ares, while the factory buildings occupied 450 square meters. The complex consisted of a small building of 14 m², another small building of 16 m², and a smaller 60 m² structure containing offices and a finished goods warehouse. The workshop was located in a two-story building.
Like his brother's factory, Nikola Devald's enterprise specialized in the production of stockings and knitted goods, including wool and cotton sweaters, woolen footwear, and similar products. Both factories continued operating until the eve of the Second World War [6, 7, 8].

2.3 Walter Bahrich Mechanical Weaving Mill, Later Textile Industry "Tibeo"

The Walter Bahrich Mechanical Weaving Mill was registered with the Basic Court in Sremska Mitrovica under business file number II Fi. 167/1934 on 30 March 1934. The registration was confirmed by the municipal authorities of Zemun on 9 March 1934. The weaving mill was located at 17 Kej 5. Novembra Street.
The owner of the weaving mill was Walter Bahrich, born in Vienna, an Austrian citizen residing at 11 Karađorđeva Street in Zemun. The location of the factory was favorable, as it was situated approximately 150 meters from the river steamship station and about one kilometer from the Zemun railway station.
The factory premises were leased from Lazar and Leposava Čuturilo, while the initial value of the machinery and equipment amounted to only 35,000 dinars. The installed power capacity of the weaving mill was 5 horsepower, and electricity was supplied by the Zemun power plant. The weaving mill was a small-scale enterprise consisting of one workshop, one small warehouse, and an office located within a private building with several additional rooms. The maximum number of employees was eight workers.
At the beginning of its operation, the weaving mill produced cvilingfuter lining fabric, with a maximum annual production capacity of 20,000 meters under full operation. For military requirements, the factory was initially capable of producing 50 meters of linen fabric per day [8].

2.4 “Paris” Knitting Factory of Vera D. Đorđević

The “Paris” Knitting Factory owned by Vera D. Đorđević was established with the approval of the Ministry of Trade and Industry, decision no. III 45766, issued on 7 December 1938, and was entered into the commercial register by a decision of the District Court in Sremska Mitrovica on 24 December 1938. The owner of the factory was Vera D. Đorđević, a housewife originally from Požarevac and the wife of lawyer Dragomir V. Đorđević from Požarevac. The factory complex, as well as the family residence, was located at 9 Tvornička Street in Zemun.

The history of this factory is particularly interesting because it had been established earlier, in 1931. The original mechanical knitting workshop was founded in that year under the name “Azriel Brothers Knitting Factory” (*Trikotaža braće Azriel*) and was registered with the Belgrade Commercial Court under no. 14,222. It developed into an industrial enterprise in 1935, following a decision of the same court under no. 5557. The owners of the factory were brothers Walter and Robert Azriel from Vienna, Austrian citizens. During its first seven years of operation, the factory worked in rented premises at 130 Kralja Aleksandra Street in Belgrade.

In 1936, the factory employed 80 adult male unskilled workers and 5 adult female unskilled workers, as well as three domestic male administrative employees and one female administrative employee. That year, the factory produced 25,000 kilograms of goods valued at 2.5 million dinars, consisting of women’s underwear and men’s shirts made of silk and cotton. In 1938, the Azriel brothers transferred the machinery and other equipment to a new location in Zemun, at 9 Tvornička Street, and in the same year re-registered the company with the District Court in Sremska Mitrovica.

The year 1938 was a significant turning point regarding the position of Jews in Europe. Due to increasing international political pressure and the deteriorating situation in the Kingdom of Yugoslavia, including Serbia, no direct state laws specifically targeting Jews, comparable to the racial laws already introduced in Germany and Italy, had yet been enacted in Yugoslavia during that year. However, following Germany’s annexation of Austria (*Anschluss*) in 1938 and the pogrom known as Kristallnacht (9–10 November 1938), antisemitic attitudes intensified throughout Europe. Official discriminatory regulations in the Kingdom of Yugoslavia were introduced somewhat later, in October 1940, through the Decree on Measures Concerning Jews in the Field of Trade and the Decree on the Registration of Jews in Secondary Schools (the so-called *Numerus clausus*), which restricted Jewish access to education and participation in trade.

These circumstances undoubtedly influenced the Azriel brothers’ decision to withdraw from the business and sell the factory to Vera D. Đorđević on 23 November 1938.

Since the factory operated under her ownership for only slightly more than two years, it is difficult to assess its overall business performance during her management. According to data from 1939, the factory employed 91 workers, including three administrative employees and three technical staff members.

With an eight-hour working day, the production capacity of the factory amounted to 60,000 overalls, 5,000 pairs of women’s underwear, 500 nightgowns, 15,000 shirts, and 100,000 meters of plain fabric. During 1939, the factory produced: 80,000 overalls, of which 60,000

were sold; 10,000 pairs of women's underwear, of which 7,000 were sold; 500 nightgowns, of which 400 were sold; 20,000 men's shirts, of which 15,000 were sold; 120,000 meters of plain fabric, of which 100,000 meters were sold. The total value of the production of these items amounted to 2,575,000 dinars [8].

2.5 "Sava" Knitting Factory of Jovan T. Janković and Brothers David and Anđelko Tajtacak

This enterprise was founded by Aleksandar Ristić in 1924 on a small scale. In 1927, it was taken over by Jovan T. Janković, who initially operated it under the name Lubomir T. Stefanović and Company. In 1928, Stefanović left the company, and the enterprise was re-registered under its new name on 3 December 1928. In 1933, the business was registered as an industrial enterprise for the production of knitted and fashionable goods under the name Janković T. Jovan and Brothers Tajtacak – "Sava" Knitting Factory (*Janković T. Jovan i braća Tajtacak – SAVA fabrika trikotaže*).

The owners of the factory were: Jovan T. Janković, born in Niš in 1882, residing in Zemun; David-Viktor I. Tajtacak, born in Belgrade in 1890; Anđelko I. Tajtacak, born in Belgrade in 1902, who was killed at the Staro Sajmište concentration camp in 1942. All three owners were citizens of Yugoslavia. In 1938, David Tajtacak died, and his heirs — his wife Sarina (born in 1902) and his son Isak (born in 1933) — withdrew from the company by selling their share to the remaining co-owners.

The factory operated at two locations on Gundulićeva Street in Zemun. The premises at number 10 housed the mechanical department, the clothing manufacturing department, and warehouses for raw and semi-finished materials. The administrative offices, stocking department, ironing department, and finished goods warehouse were located at number 6 on the same street [7, 9].

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Figure 3: Advertisement for the Sava Factory, published in the daily newspaper *Politika* on 15 October 1927.

2.6 “Javor” Mechanical Weaving Mill of Vuković, Bešević and Stojković

This mechanical weaving mill received a temporary operating permit on 5 November 1938, followed by a permanent permit on 13 May 1939 under registration number 19024. The founding capital amounted to 810,000 dinars, equally divided among the three owners: Ranisav Bešević (born in 1903 in Ivanjica), Vojislav Vuković (born in 1906 in Ivanjica), and Milojko Stojković (born in 1912 in Bogova). Prior to these registrations, the enterprise operated under the names “Avala” Mechanical Weaving Mill – Bešević Ranislav and Živković Dušan, and earlier as “Avala” Mechanical Weaving Mill – Ranisav Bešević.

The weaving mill began operating in its new building in Zemun in March 1939. Initially, it employed six workers, while the planned expansion envisaged a workforce of 20 workers, three technical employees, and one administrative employee. The factory complex was located at 27 Tošin Bunar Street. Due to limited space, an auxiliary clothing manufacturing department was established in Belgrade at 18 Kralja Petra Street.

The weaving mill produced silk and cotton scarves, initially using twelve looms, and also carried out the finishing and garment production of these products. The production capacity of the factory was relatively small. During one year of operation, based on an eight-hour working day, it could process 3.5 tons of cotton and 7.5 tons of artificial silk yarn, making it one of the smaller textile enterprises in Zemun. After two years, the factory was relocated to Belgrade, at 37 Živka Davidovića Street, where it was expanded and modernized. It was subsequently re-registered under the name “Javor” Mechanical Weaving Mill – Vuković and Stojković [10].

2.7 “Avala” Mechanical Weaving Mill of Radosav V. Bešević

This mechanical weaving mill was initially established solely under the name of Radosav Bešević. It received an operating permit no. 46066/35 on 4 February 1936 and was registered with the Basic Court in Sremska Mitrovica on 12 December 1936. The company headquarters were located at Despot Đurđ Street. The founding capital amounted to 300,000 dinars, of which 200,000 dinars were invested in the rental of the building and production facilities, while 100,000 dinars represented working capital and funds for the purchase of raw materials. The initial maximum workforce consisted of two administrative employees and fourteen workers.

At the end of 1937, Dušan Živković entered into partnership with Bešević, after which the enterprise received a new operating permit under a new name and at a new location, 50 Dobanovačka Street. At that time, the invested capital increased to 4,000,000 dinars, while the number of workers grew from fourteen to an average of forty employees, although at certain periods it reached as many as sixty. The production capacity of the factory, expressed in linear meters and based on an eight-hour working day, amounted in 1937 to 162,000 meters of natural and artificial silk fabrics. In 1939, the invested capital of the company increased further, reaching a total of 40,000,000 dinars. Under an eight-hour working regime, the annual consumption of raw materials amounted to 65,000 kilograms of artificial silk and 215 kilograms of cotton yarn, while the factory sold 400,000 linear meters of artificial silk fabric.

In 1941, Radosav Bešević's brother, Ranisav Bešević, joined the company as a full partner. When it became clear that Zemun would become part of the territory controlled by the Independent State of Croatia (NDH), the partners transferred most of the machinery and equipment to Belgrade in September 1941 and continued operations under a new company name, "Bešević Brothers and Živković" [11].

2.8 Dejan Frušić Silk Fabric Factory

The Silk Fabric Factory began operations following approval issued by the Ministry of Trade and Industry of the Kingdom of Yugoslavia under decision no. 14050/37 dated 19 April 1937. The owner, Dejan Frušić, was born in the village of Tovarnik, Šid district. The invested capital for the establishment of the enterprise amounted to 900,000 dinars, and the company headquarters were located at 65 Tošin Bunar Street in Zemun.

The factory's full annual production capacity, based on an eight-hour working day, amounted to 36,000 meters of artificial silk fabric, which was subsequently sent to other enterprises for finishing and dyeing processes. In addition to artificial silk production, in the event of war the factory was capable of producing 40,000 linear meters of cloth and bandage material within the same period. At the beginning of its operation, the factory employed one skilled worker, two qualified designers, and twelve weavers [10].

2.9 First Yugoslav Silk Goods Weaving Company JSC from Osijek, Zemun Branch

The First Yugoslav Silk Goods Weaving Company Joint-Stock Company (*Prva jugoslavenska tkaonica svilene robe d.d.*) from Osijek was established in 1930. In 1938, the factory received approval from the Ministry of Trade and Industry of the Kingdom of Yugoslavia, dated 18 October 1938, to establish a branch in Zemun, which was managed by the company supervisor Vilim Štraus.

In May 1939, the factory received permission to commence operations in its new premises, located in a building owned by S. Mojsilović and E. Kajon. During the same year, the Zemun branch employed between 39 and 58 workers.

The production capacity of the branch included the processing of 6.098 tons of artificial silk yarn. In 1939, the branch produced 158,326 square meters of artificial silk fabric, of which 154,967 square meters were sold [10].

2.10 Dingarac, Stojanović and Goločevac Textile Industry

The factory was established in 1927 with 50 looms. By 1929, this number had increased to 100, and by 1934 to 146 looms, a figure that remained unchanged until 1939.

The enterprise was founded with a capital investment of 5,000,000 dinars. Its owners were Rista Dingarac, born in Vranje; Petar Stojanović, born in Leskovac; and Jovan Goločevac, born in Vranje and residing in Skopje, who later also moved to Belgrade. The factory buildings and the management offices were located at 18 Tvornička Street in Zemun.

Under normal operating conditions, with an eight-hour working day, the factory employed two administrative employees and 75 workers. During periods of increased production at the end of the 1930s, the workforce could increase to approximately 90 employees.

The factory produced cotton cloth (*American*), with an annual production capacity of 200,000 kilograms or 1,000,000 meters based on an eight-hour working schedule.

In 1939, the factory produced 756,000 square meters of plain cotton fabrics with up to 50 threads per square centimeter, while sales amounted to slightly less, totaling 711,786 square meters [12].

2.11 Hadži Bošković Brothers Textile Industry

The factory was established in 1929 and registered by the municipal authorities of Zemun under no. O. 721 on 19 August 1932. The factory was located at 16/18 Naum Savić Street, and its owners were the brothers Jovan, Trajko, Ljubomir, and Dragan Hadži Bošković, all born in Skopje. At the beginning of its operation, the factory possessed 144 automatic looms powered by electricity. Initially, the enterprise had the capacity to employ five master craftsmen and 115 workers. Based on an eight-hour working day, the factory's production capacity amounted to 1,008,000 meters of plain cotton fabric (*American*), with a thread count of up to 50 threads per square centimeter. On 1 March 1938, the factory was leased by Borislav P. Ristić and Milošević, who continued operations under the new name Borislav P. Ristić and Milošević Textile Industry. At the time of the takeover, the value of the factory amounted to 3,000,000 dinars in real estate, buildings, and machinery, and 1,500,000 dinars in goods and other inventory. During their management, particularly in 1938 and 1939, the volume of production and sales remained at a similar level to that achieved under the previous owners [12].

2.12 First Serbian Velour and Plush Factory of Svetislav N. Mitić

The factory owned by Svetislav N. Mitić was established before the First World War, in 1910. After the war, it was officially registered in 1922 under registration number 8150, dated 23 August. The factory was located at 3 Tvornička Street in Zemun, which also served as the company headquarters. Based on an eight-hour working day, the production capacity amounted to 100,000 meters of cotton fabric and 15,000 meters of wool fabric.

In 1939, the factory had a value of 4,018,285 dinars in machinery and equipment, 3,500,000 dinars in buildings and inventory, and 6,455,199 dinars in raw materials and finished products. Under full operating capacity, the factory could employ approximately 150 workers. The factory specialized exclusively in the production of krimer (astrakhan) made from jute and wool, which was used for manufacturing šubare (traditional fur-style caps), as well as plush made from wool and artificial silk, and tailoring accessories such as rošar and plastic materials.

In the same year, 1939, the factory processed: 16,000 square meters of artificial silk plush; 1,600 square meters of wool krimer; 5,000 square meters of jute krimer. It produced 3,000 dozen šubare made from krimer, of which 2,300 dozen were sold [13].

2.13 “Tekstilind” Knitting and Other Textile Products Factory of Rudolf Klopfer

The factory was established in 1934 and received an operating permit in the same year under no. 215/1934 from the Administration of the Municipality of Belgrade, Zemun Division. The first owners were Moritz Wasenstein, born in Sarajevo, and Erwin Mayer, born in Worms. The factory's production facilities were located at 5 Tvornička Street in Zemun, where it manufactured underwear made from silk and cotton yarn.

In 1938, the factory was taken over by Rudolf Klopfer, who relocated it to 184 Cara Dušana Street. The enterprise officially resumed operations at the new location on 2 January 1939. The factory employed 70 female workers and produced cotton, rayon, and silk knitwear. Shortly before the outbreak of the Second World War, Klopfer invested significant funds in new machinery in order to modernize and expand production [14].

2.14 Branko Tokin Textile Industry

The Branko Tokin Textile Industry was established in 1937. The company was registered with the District Court in Sremska Mitrovica on 31 December 1936, while the operating permit was granted by the Ministry of Trade and Industry in February 1937. The owner of the company was Branko Tokin, a Belgrade industrialist born in Pančevo. The company was registered at 32 Tvornička Street in Zemun. This was an exceptionally favorable location for industrial facilities, as the factory was situated directly alongside the railway line, while the distance to both the railway station and the river port was approximately one kilometer. In May 1936, Branko Tokin conceived the idea of establishing a factory dedicated exclusively to the production of white cotton cloth, which represented an innovation in the textile sector of this region. He invested his own capital in the establishment of the enterprise.

The factory complex covered an area of 1,620 square meters. For production purposes, the factory acquired the most modern weaving machinery, which was fully automated, as well as all necessary equipment for the bleaching department and finishing operations, including the final treatment of cotton fabrics after weaving and bleaching. The factory was equipped according to modern industrial standards. During the first year of operation, emphasis was placed on training personnel and creating the necessary conditions for the production of high-quality fabrics. A complete water-softening installation was introduced, together with equipment for regulating humidity and temperature. The factory also installed its own electric power plant to supply the machinery located in the weaving department.

The factory complex included an apartment for the manager, company offices, a room intended as a workers' dining area, and storage facilities for raw materials, semi-finished products, and finished goods. The factory operated throughout the entire year. The weaving department worked in two shifts, while the bleaching department operated in one shift. The factory had the capacity to employ up to 120 workers.

Tokin personally managed the factory, while the production process was supervised by engineer Stevan Hiršenberger, born in Budapest. The investments and efforts made produced successful results relatively quickly. The first-class fabrics manufactured by the factory soon gained recognition throughout the entire country. The factory produced white cotton cloth known as chiffon, which was used for making bed linen and men's and women's underwear. In addition, the factory produced white American cotton cloth (*amerikan*) in various widths and qualities, representing a significant novelty among textile products at the time.

Unfavorable market conditions, the practice of selling goods on deferred payment terms, and the accumulation of large quantities of yarn reduced the profitability of the factory during the second half of the 1930s. As a result, Branko Tokin was forced to enter into a

partnership arrangement in 1938. He reached an agreement with Predrag Nikolić, a long-time director of the Vlada Teokarović and Company Woolen Textile Industry in Paraćin. Mr. Nikolić was the nephew of Vlada Teokarović, and it was expected that his extensive experience and expertise would contribute both to improving production processes and to achieving better market placement of the products. According to archival documentation, in 1940 the company gradually began preparing to shift toward the production of military materials, including gauze, cloth, and similar products [12].

2.15 “Stella” Textile Industry Joint-Stock Company

The “Stella” Textile Industry Joint-Stock Company was established in March 1937. The company headquarters were located on Vlajkovićeva Street, while the production facilities were situated in Zemun, at 72 Tvornička Street. The capital invested in the establishment of the company originated from Romanian, French, and Yugoslav sources. The initial shareholders of the company included Romanian citizens Yaridijan Mikerdić and Nahmijas Moscu, each holding 6,250 shares, as well as Yugoslav citizens: Dragan Milenčić (2,000 shares), Ljubomir Hadži Bošković (500 shares), Dragan Hadži Bošković (200 shares), Vladimir Zakić (750 shares), and Milan Belanović (40 shares).

Figure 4: Aerial panorama of Zemun, 1930s. From the private collection of Miloš Jurišić

The factory began operations in March 1938. It was a newly constructed industrial facility equipped with new machinery. The factory complex occupied a plot of land measuring 9,553 square meters, while the factory buildings covered an area of 2,737 square meters.

The machinery and equipment were entirely new and had been imported from Germany. Cotton was used as the primary raw material, and the company operated as a spinning mill processing cotton yarn intended for weaving by industrial enterprises.
Cotton was imported primarily from the United States, while domestic cotton supplied only about 2% of production requirements. The factory's products were manufactured mainly for the needs of the Ministry of Army and Navy. Under peacetime conditions, production operated in a single eight-hour shift and employed approximately 80 workers. The factory director was the Romanian engineer Mikerdić Yaridijan.
The company held a license for cotton spinning with a capacity of 6,000 spindles.
The enterprise was nationalized after the Second World War and later became one of the subjects addressed within the framework of the 1951 French-Yugoslav Agreement on Compensation for French Interests Nationalized in Yugoslavia [12].

2.16“Alda” Mechanical Weaving Mill, Joint-Stock Company

“Alda” Mechanical Weaving Mill, a joint-stock company, was established in 1929. The registration of the weaving mill was carried out with the District Court in Zemun. The company headquarters were located in Zemun, at 140 Tošin Bunar Street. The company's production program included cotton fabrics, known as American cotton fabrics (*amerikan*), produced in various qualities and widths up to 150 cm, as well as terry towels and terry cloth fabrics for bathing purposes.
The raw materials used in the production process were mainly imported. Cotton yarn was imported from Italy and Czechoslovakia, wool yarn from Belgium, while machinery and equipment were sourced from Austria, Belgium, Italy, and Czechoslovakia.
The weaving mill operated throughout the entire year, with working hours adjusted according to production requirements. By the mid-1930s, when production and product distribution had already expanded, the factory operated in two shifts, totaling 58 working hours per week. Under normal operating conditions, the factory employed 72 workers, while continuous operation required a workforce of up to 210 employees.
The production facilities were financed through share capital. By the mid-1930s, the factory consisted of several departments: a terry weaving department; a department for the production of *amerikan* cotton cloth; a fabric inspection and measuring department; a warp preparation department;a finishing department; a boiler house and furnace facility. The factory complex also included accommodation for a security guard. The company director was Josif Almuli. The shareholders of the company came from prominent Jewish merchant and intellectual families who were related to one another. In the mid-1930s, the distribution of shares was as follows: David Alvy, banker, 10 shares; Samuel Davičo, commercial agent, 500 shares; David Mevorah, commercial agent, 10 shares; David Alkalaj, lawyer, 10 shares; Jakov Pijade, merchant, 10 shares; Josif Almuli, industrialist, 10 shares; Rejna Almuli, 200 shares; Ela Eškenazi, 200 shares; Maks Koen, merchant, 10 shares; Dr. Isak Eškenazi, physician, 200 shares; Dr. Žarko Almuli, physician, 10 shares; Samuil Najman, merchant,10 shares; Leja Almuli, 200 shares; Vera Eškenazi, 100 shares; Ivan Almuli, industrialist, 10 shares.

Immediately before the outbreak of the Second World War, plans were made for the factory to operate for the needs of national defense in the event of mobilization [12].

2.17 “Tekstil” Woolen Fabrics Factory of Milorad Stojadinović

The “Tekstil” Woolen Fabrics Factory, owned by Milorad Stojadinović, received an operating permit in May 1933. The company was registered in June of the same year with the District Court in Zemun. The factory was registered at 142 Tošin Bunar Street. At the time of registration, both the factory and the land on which it stood were owned by Milorad Stojadinović. The factory building itself had been constructed in 1927 and was originally owned by Dragoljub Stojadinović, but his enterprise was liquidated in 1933. The factory was located only half a kilometer from the Zemun river port and three kilometers from the railway station.

The factory produced šajak (coarse woolen cloth), čoja (wool broadcloth), officer-grade broadcloth, blankets, and plain woolen fabrics. It consisted of several departments: a department for the preparation of artificial wool; a spinning mill; a weaving department; a warping department; a finishing department; a workshop.

The factory did not possess a drying facility. The complex also included accommodation for a security guard and two employees. Regarding the machinery, half of the equipment was owned by Goldberg Volf Simhe. The factory operated seasonally, from March until December. Working hours consisted of an eight-hour shift or two shifts, depending on the volume of orders. The production capacity of the factory amounted to 4,000 meters of woolen fabric when operating in one shift, or 8,000 meters when operating in two shifts. Under normal operating conditions, the factory employed a maximum of five administrative staff members and 110 workers. During periods of full production capacity, the workforce increased by approximately 50 percent. In addition to domestic labor, the factory also employed foreign skilled workers, primarily from Poland.

Immediately before the outbreak of the Second World War, the enterprise was contracted for military production and was expected to manufacture blankets for the needs of the Ministry of Army and Navy [12].

3. CONCLUSION

The development of industry in Zemun during the interwar period was rapid and intensive. In 1919, when the new state union was established, approximately forty different enterprises were registered in the territory of Zemun, most of which were organized on a scale that only slightly exceeded artisanal production.

The strong industrial expansion that followed in the subsequent years was primarily influenced by the protective tariffs introduced by the state, as well as by the incentives and privileges granted by the municipality to business owners. According to the Customs Law of 1925, which significantly contributed to the development of the textile industry, all imported goods, machinery, and equipment were subject to high customs duties. At the same time, customs rates were increased for finished textile products imported from abroad. This created opportunities for domestic manufacturers to reorganize production,

introduce rationalization and modernization measures, and gain control over the domestic market with their own products.

In addition, the Municipality of Zemun, recognizing industrial development as crucial for the economic recovery of the city, pursued an intensive policy of attracting industrialists and investment. As a result, after the First World War, several Belgrade industrialists relocated some of their factories to the territory of the Municipality of Zemun.

With regard to the textile industry, one of the most significant enterprises was the Woolen Fabrics Factory of Živojin Vukojičić and Sons, established in 1927, which primarily specialized in the production of broadcloth and blankets. Immediately before the Second World War, the value of this factory amounted to nearly 15 million dinars.

Other textile enterprises located in Zemun were either established with private capital or organized as joint-stock companies, combining domestic and foreign investment. Most possessed their own buildings and production facilities, and some also had their own power plants. These enterprises manufactured a wide range of products, including cloth, cotton fabrics, cotton and silk knitwear, yarn, blankets, broadcloth, coarse woolen fabrics, terry cloth, towels, and terry fabrics.

All of these enterprises played an important role in the industrial development of Zemun during the interwar period and represented a solid foundation for the further development of the textile industry after the Second World War.

Although many factories suffered certain levels of damage during the war, the majority were nationalized after the war, and their production facilities, capacities, machinery, and equipment were incorporated into post-war industrial production. In accordance with the Law on the Nationalization of Private Enterprises of 1946, all private enterprises of general state and republican importance, including those in the textile industry, were transferred into state ownership.

Thus, after the Second World War, Zemun's textile enterprises were nationalized. The Woolen Fabrics Factory of Živojin Vukojičić and Sons, together with several other factories, became part of the enterprise "Ivan Milutinović", established in 1948.

A section of the "Danubius" Textile Industry became part of the "Staljingrad" Textile Factory, which later developed into the Belgrade Cotton Combine. The "Stella" Textile Industry Joint-Stock Company, "Alda" Mechanical Weaving Mill, Branko Tokin Textile Industry, and Dingarac, Stojanović and Goločevac Textile Industry became part of the "Sutjeska" Textile Industry in Zemun, established after the Second World War, which later became part of the "Staljingrad" Cotton Factory. The First Serbian Velour and Plush Factory of Svetislav N. Mitić, together with the "Plaros" factory, became part of the "Stevan Dukić" Textile Industry, among other examples.

The interwar development of the textile industry in Zemun, together with municipal incentives and favorable customs policies, created a strong foundation for the further development of textile production after the Second World War within socialist Yugoslavia. Although nationalization deprived the former owners of their enterprises — some of whom had emigrated or had even lost their lives during the war — the production capacities were incorporated into new textile enterprises created through the consolidation of existing factories. Through subsequent reorganizations and transformations, these enterprises

continued to operate and manufacture textiles and knitwear for decades, making a significant contribution to the economic development of socialist Yugoslavia [15, 26, 17, 18].

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SESSION I

TECHNOLOGIES

9. Međunarodna naučna konferencija
*„**Savremeni trendovi i inovacije u tekstilnoj industriji**“*
17-18. septembar 2026. Beograd, Srbija

MECHANICAL PERFORMANCE OF SOLAR-PROTECTIVE FABRICS MANUFACTURED FROM VOLCANIC MINERAL-MODIFIED POLYESTER YARNS

Scientific paper
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ABSTRACT: *The increasing demand for functional textiles has led to extensive research on the incorporation of mineral-based additives into synthetic fibers to enhance their performance characteristics. In this study, the effects of volcanic mineral additives on the mechanical properties of polyester yarns and woven fabrics intended for solar protection applications were investigated. Cerium oxide-and silicon oxide-based masterbatches were prepared using a PBT carrier and incorporated into polyester during the melt-spinning process to produce partially oriented yarns (POY). The POY yarns were subsequently textured to obtain draw textured yarns (DTY), which were then used in the production of curtain fabrics.The tensile properties, boiling shrinkage, and crimp contraction behaviour of the yarns were evaluated, while the mechanical performance of the woven fabrics was assessed through tensile strength and tear strength tests conducted in both warp and weft directions. The results demonstrated that the incorporation of volcanic mineral additives influenced the structural and mechanical behaviour of polyester yarns and fabrics. Fabric test results revealed that cerium oxide-added polyester fabrics exhibited higher breaking strength values than silicon oxide-added fabrics. Tear strength performance was affected by both fabric direction and additive type. While fabrics containing 2% silicon oxide showed lower tear strength in the warp direction, they exhibited higher tear strength in the weft direction. Overall, the findings demonstrate that volcanic mineral additives can be successfully incorporated into polyester yarn structures and significantly influence the resulting yarn and fabric properties*

Keywords: *Polyester yarn, volcanic minerals, cerium oxide, silicon oxide, technical textiles, mechanical properties.*

MEHANIČKE PERFORMANSE SOLARNO-ZAŠTITNIH TKANINA PROIZVEDENIH OD POLIESTARSKIH PREĐA MODIFIKOVANIH VULKANSKIM MINERALIMA

APSTRAKT: *Rastuća potražnja za funkcionalnim tekstilom dovela je do opsežnih istraživanja o ugradnji aditiva na bazi minerala u sintetička vlakna radi poboljšanja njihovih karakteristika performansi. U ovoj studiji ispitani su efekti aditiva vulkanskih minerala na mehanička svojstva poliestarskih pređa i tkanina namenjenih za primenu u zaštiti od sunca. Masterbačevi na bazi cerijum-oksida i silicijum-oksida pripremljeni su korišćenjem PBT nosača i ugrađeni u poliestar tokom procesa predenja rastopa kako bi se proizvele delimično orijentisane pređe (POI). POI pređe su potom teksturirane da bi se dobile teksturirane pređe (DTI), koje su zatim korišćene u proizvodnji tkanina za zavese. Procenjena su svojstva zatezanja, skupljanje pri ključanju i karakteristike kovrdžavosti, dok su mehaničke performanse tkanina procenjene testovima zatezne čvrstoće i čvrstoće na kidanje sprovedenim u pravcu osnove i potke. Rezultati su pokazali da je ugradnja vulkanskih mineralnih aditiva uticala na strukturno i mehaničko ponašanje poliesterskih pređa i tkanina. Rezultati ispitivanja tkanina pokazali su da poliesterske tkanine sa dodatkom cerijum oksida pokazuju veće vrednosti čvrstoće na kidanje od tkanina sa dodatkom silicijum oksida. Na performanse čvrstoće na kidanje uticali su i smer tkanine i vrsta aditiva. Dok su tkanine koje sadrže 2% silicijum-oksida pokazale manju čvrstoću na kidanje u pravcu osnove, pokazale su veću čvrstoću na kidanje u pravcu potke. Generalno, nalazi pokazuju da se vulkanski mineralni aditivi mogu uspešno ugraditi u strukture poliestarskih pređa i značajno uticati na rezultujuća svojstva pređe i tkanine.*

Ključne reči: *Poliestarska pređa, vulkanski minerali, cerijum-oksid, silicijum-oksid, tehnički tekstil, mehanička svojstva.*

1. INTRODUCTION

The use of additives in polyester yarns is a widely adopted approach both to improve the processability of the polymer during production and to impart functional properties to the final product. In the textile industry, additives are extensively utilized to achieve multifunctional performance, including ultraviolet (UV) protection, thermal resistance, antibacterial activity, flame retardancy, antistatic behaviour, and improved mechanical properties. These additives are typically incorporated into the polymer matrix in masterbatch form and processed via the melt spinning technique, enabling uniform dispersion within the fiber structure. Additives used in polyester (PET) yarns can generally be classified into inorganic, organic, and hybrid (organic–inorganic) systems. Inorganic additives such as titanium dioxide (TiO_2), zinc oxide (ZnO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), cerium oxide (CeO_2), and nanoclay structures are widely employed to enhance UV shielding, thermal stability, and abrasion resistance. These particles function primarily through UV absorption and scattering mechanisms, thereby improving the protective performance of textile materials. For instance, TiO_2 and ZnO

nanoparticles have been reported to enhance UV protection and opacity in polyester fibers, while nano-silica contributes to improved mechanical strength and surface hardness [1-5] Organic additives generally include antibacterial agents, pigments, dyes, and organic flame-retardant compounds. Among these, silver-based antimicrobial systems (Ag^+-containing structures) are particularly effective in inhibiting microbial growth on textile surfaces, thereby enhancing hygienic performance. Additionally, phosphorus-based flame retardants are commonly used to improve the combustion behaviour of polyester-based materials [4-7]. In recent years, nanoscale and hybrid additive systems have gained increasing attention due to their ability to enhance functional performance even at low loading levels. The high surface area of nanoparticles enables improved interaction with the polymer matrix, leading to synergistic effects in UV protection, thermal management, and mechanical reinforcement applications. However, the type and concentration of additives, together with fiber dispersion quality and spinning parameters, significantly influence the final performance of the resulting textile structures [3-6].

Solar protection properties in textiles can be achieved either through the use of functionalized yarns containing additives or through post-production surface finishing and coating techniques. However, the incorporation of functional materials directly into the fiber structure provides a more durable and long-lasting performance compared to surface treatments, which may degrade over time due to washing or environmental exposure. Several studies in the literature have investigated the effects of additives on the physical and mechanical properties of polyester fibers and fabrics. Previous research has demonstrated that the type, particle size, concentration, and dispersion quality of additives significantly affect tensile strength, elongation, stiffness, abrasion resistance, and thermal stability. However, studies specifically focusing on volcanic mineral-modified polyester yarns remain limited, particularly in the context of solar-protective technical fabrics. Therefore, further investigation is necessary to better understand the relationship between volcanic mineral incorporation and the mechanical performance of woven or knitted textile structures intended for outdoor applications [7-11]. In this study, volcanic mineral-added polyester yarns were used to produce curtain fabrics with inherent solar protection functionality. The aim of the study is to evaluate the mechanical properties of these technical fabrics in relation to different types and concentrations of mineral additives. It is expected that integrating volcanic minerals such as cerium oxide- and silicon-based compounds into the fiber structure will contribute to the development of advanced functional textiles with enhanced durability and solar protection performance.

2. MATERIAL AND METHOD

Granule-form masterbatches containing micro-materials with a PBT carrier were prepared by SETAŞ. The masterbatch preparation process was carried out using industrial production methods suitable for synthetic yarn manufacturing processes. In the first stage, granule-form masterbatches containing cerium oxide and silicon oxide micro materials were prepared separately. Subsequently, the obtained granule-form masterbatches and granule-form PET polymer were blended at various ratios and subjected to the extrusion

process. In this way, the production of a volcanic mineral-added composite masterbatch was targeted. One of the masterbatches was prepared with a composition of 10% cerium oxide and 90% PBT, while the other was prepared with a composition of 20% silicon oxide and 80% PBT. Partially oriented Volcanic Mineral added polyester yarns with were produced with different masterbatch ratios (%1, %2) where the fiber cross sections were selected as 'w' cross section. Polyester yarn production trials were carried out using a melt-spinning machine available at the yarn manufacturing facilities of Karesi Polyester A.Ş. POY polyesters were converted into draw textured yarns (DTY). The tensile properties for POY and DTY's were measured by using Uster Tensojet while boiling shrinkage (%), crimp contraction (%) results were obtained from Texturmat device. The experimental design of the produced Volcanic mineral added polyester POY and DTY is revealed in Table 1. Drapery woven fabrics produced from volcanic mineral additive yarns were exposed to fabric tensile and tearing strength test by using Titan Device according to EN ISO 13934-1 and EN ISO 13937-2 standards respectively. Fabric parameters are revealed in Table 2.

Table 1: Experimental Design

POY type	POY code	Masterbatch Ratio (%)	"Granule-form masterbatches containing volcanic minerals	DTY (Textured yarn code)
Conventional Polyester	P1	-	-	D1
Cerium Oxide Added Polyester	P2	1 %	10% Cerium Oxide 90 % PBT	D2
Silicon Oxide Added Polyester	P3	1 %	20% Silicon Oxide 80 % PBT	D3
Silicon Oxide Added Polyester	P4	2 %	20% Silicon Oxide 80 % PBT	D4

Table 2: Fabric parameters

Fabric code	**Warp Yarn (denier/filament)**	**Weft Yarn (denier/filament)**	**Warp density (threads/cm)**	**Weft Density (threads/cm)**	**Fabric weight (g/m^2)**
F1	100/36	300/36 polyester	90	30	273
F2	100/36 Cerium Oxide added polyester (0.001)	300/36 polyester	90	30	253
F3	100/36 Silicon Oxide added polyester (0.001)	300/36 polyester	80	30	227
F4	100/36 Silicon Oxide added polyester (0.002)	300/36 polyester	80	30	231

3. RESULTS AND DISCUSSIONS

Yarn Properties

The tensile properties, boiling shrinkage (%) and crimp contraction ratio (%) results of the POY and DTW (Draw textured yarns) are revealed in figure 1 and figure 2 respectively.

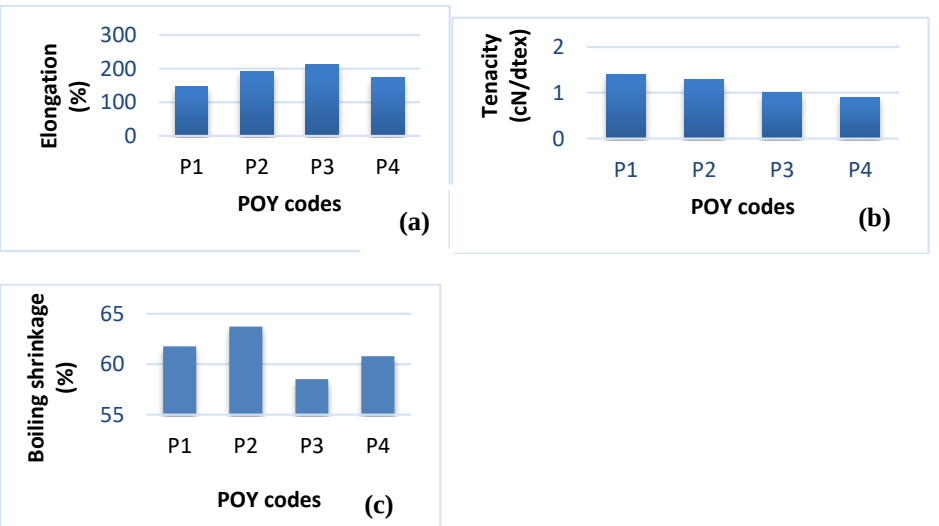
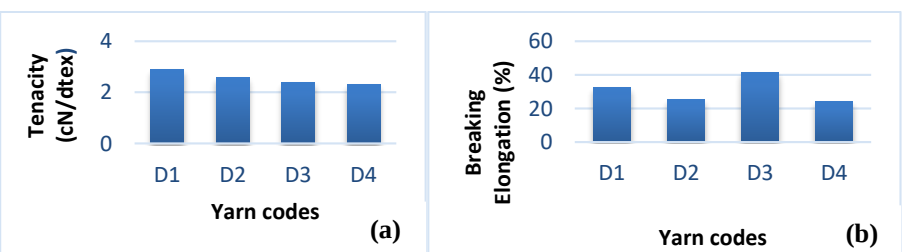


Figure 1. Elongation (a), tenacity (b) and boiling shrinkage (c) results of volcanic mineral added POYS.



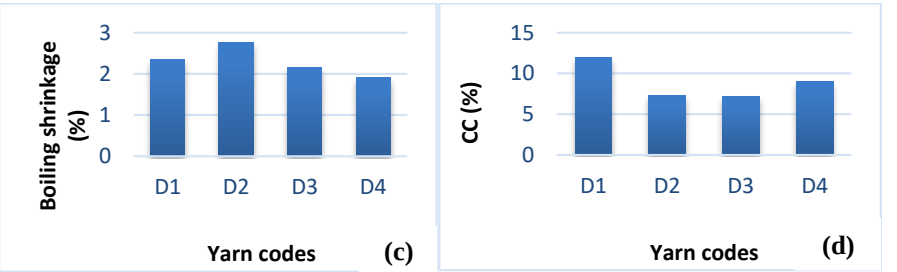


Figure 2: Tenacity (b), elongation (b), boiling shrinkage (c) and crimp contraction (d) results of volcanic mineral added textured yarns

When the Figure 2 is observed; The tensile strength values of the POY yarns tended to decrease with increasing cerium oxide concentration. This behaviour may be attributed to the disruption of polymer chain continuity and the formation of micro-scale stress concentration points caused by inorganic particles. Similar tendencies were observed in DTY yarns, although the texturing process partially altered the magnitude of the effect. Figure 2c presents the boiling shrinkage values of the DTY yarns produced with different additive concentrations. The highest boiling shrinkage was observed for sample D2 (approximately 2.75%), while the lowest value was obtained for D4 (approximately 1.90%). The results indicate that the additive concentration affects the dimensional stability of the textured yarns. While a moderate additive level appears to increase the residual internal stresses within the yarn structure, higher additive concentrations tend to reduce boiling shrinkage, suggesting improved structural stability and reduced molecular relaxation during thermal treatment. This behaviour may be associated with the interaction of cerium oxide particles with the polyester matrix and their influence on chain mobility and crystallization behaviour. When the crimp contraction of the yarns were observed (Figure 2d), the highest value was obtained from D1 coded yarns while minimum value was obtained from D2 coded yarns.

Fabric properties

The average breaking strength and tear strength values obtained from the tests conducted in both the warp and weft directions of the fabrics used in the study are presented in Figures 3 and 4 respectively. According to figure 3, breaking strength values in warp wise were generally higher than those in weft wise. Breaking strength of the fabrics produced from Cerium oxide added polyester yarns were higher than those produced from Silicon Oxide added polyester yarns. As figure 4 is analysed, it is understood that tear strength results were higher in weft wise among all samples. Fabrics produced from Silicon Oxide (2%) added polyester yarns (F4) revealed lower tear strength in warp wise but higher in weft wise.

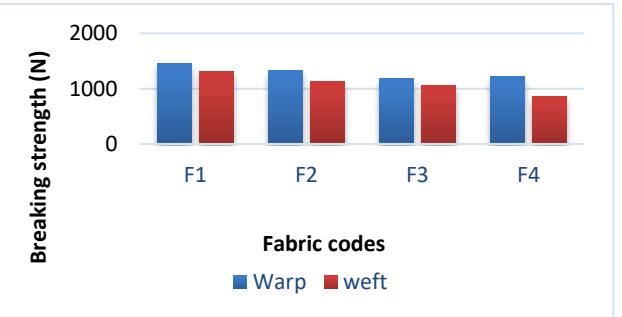


Figure 3: Breaking strength of fabrics

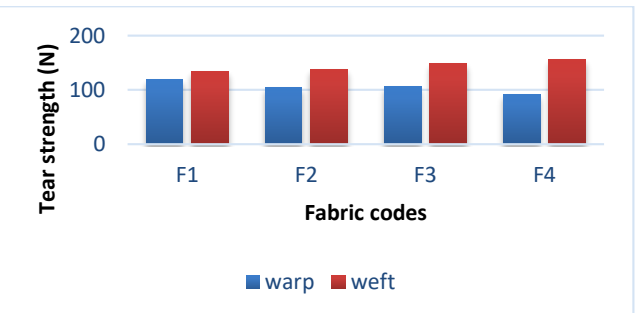


Figure 4: Tear strength of fabrics

3. CONCLUSION

In this study, the effects of cerium oxide and Silicon Oxide-based volcanic mineral additives on the properties of polyester yarns and woven fabrics were investigated. Volcanic mineral-added polyester POY yarns were successfully produced and subsequently converted into textured yarns. The tensile, and mechanical performance properties of both yarns and fabrics were evaluated.

The results showed that the incorporation of mineral additives affected the tensile and physical properties of polyester yarns. Compared to conventional polyester yarns, the addition of cerium oxide and silicon oxide particles generally caused a reduction in yarn tenacity, which may be attributed to the disruption of polymer chain continuity and the formation of stress concentration points within the fibre structure. Furthermore, the boiling shrinkage and crimp contraction values of textured yarns were influenced by both the type and concentration of the additives, indicating changes in molecular mobility and structural stability. Fabric test results revealed that fabrics produced from cerium oxide-added polyester yarns exhibited higher breaking strength values than those produced from silicon oxide-added polyester yarns. Tear strength performance varied depending on the fabric direction and additive type. While silicon oxide-added fabrics showed relatively lower tear strength in the warp direction, higher tear strength values were observed in the weft direction. Overall, the findings demonstrate that both cerium oxide and silicon oxide

additives can be successfully incorporated into polyester yarn structures and significantly influence the resulting yarn and fabric properties. The study provides a useful basis for the development of functional textile materials intended for solar protection and thermal comfort applications. Future studies will focus on evaluating the solar radiation transmission, UV protection performance, thermal insulation behaviour, and durability characteristics of fabrics produced from volcanic mineral-added polyester yarns.

ACKNOWLEDGEMENT
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TOWARD A YARN GENOME: A UNIVERSAL FRAMEWORK FOR DESCRIBING TEXTILE YARN STRUCTURE

Review scientific paper
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ABSTRACT: *Yarn structure is one of the most important factors influencing the mechanical, physical, and functional performance of textile products. Conventional yarn characterization primarily relies on individual parameters, including diameter, twist, hairiness, linear density, evenness, and tensile properties. Although these descriptors provide valuable information, none can independently represent the complex three-dimensional architecture of yarn or fully explain its structure–property relationships. Recent advances in digital imaging, three-dimensional characterization, and artificial intelligence have enabled the extraction of multiple structural features simultaneously, creating opportunities for more comprehensive yarn evaluation. This review introduces the concept of a Yarn Genome, a universal framework that integrates conventional and emerging structural descriptors into a multidimensional representation of yarn identity. Inspired by the Materials Genome Initiative, the proposed framework combines twist, diameter variation, fiber orientation, porosity, hairiness, surface chemistry, and structural complexity quantified using image-based descriptors such as entropy, fractal dimension, and texture analysis. The review summarizes conventional yarn descriptors, discusses modern characterization technologies, and highlights their roles in defining the proposed Yarn Genome. Finally, future perspectives involving artificial intelligence, digital twins, smart spinning systems, standardized Yarn Genome databases, and digital textile passports are presented. The proposed framework provides a conceptual foundation for next-generation yarn characterization, supporting predictive textile engineering, intelligent quality control, and data-driven textile manufacturing.*

Keywords: *Yarn Genome; yarn structure; structural descriptors; digital image analysis; textile characterization; artificial intelligence; porosity; fiber orientation; hairiness.*

KA KONCEPTU GENOMA PREĐE: UNIVERZALNI OKVIR ZA OPISIVANJE STRUTURE TEKSTILNE PREĐE

APSTRAKT: *Struktura pređe predstavlja jedan od najvažnijih faktora koji utiče na mehaničke, fizičke i funkcionalne karakteristike tekstilnih proizvoda. Konvencionalna karakterizacija pređe uglavnom se zasniva na pojedinačnim parametrima, uključujući*

prečnik, uvoj, dlakavost, finost, neravnomernost i zatezna svojstva. Iako ovi deskriptori pružaju značajne informacije, nijedan od njih pojedinačno ne može u potpunosti da opiše složenu trodimenzionalnu arhitekturu pređe niti da objasni međusobni odnos između njene strukture i svojstava. Nedavni napredak u oblasti digitalnog snimanja, trodimenzionalne karakterizacije i veštačke inteligencije omogućio je istovremeno izdvajanje većeg broja strukturnih karakteristika, čime su otvorene nove mogućnosti za sveobuhvatniju analizu pređe. U ovom preglednom radu predstavljen je koncept Genoma pređe (Yarn Genome), univerzalnog okvira koji integriše konvencionalne i savremene strukturne deskriptore u višedimenzionalni prikaz identiteta pređe. Inspirisan inicijativom Materials Genome Initiative, predloženi okvir objedinjuje uvoj, varijaciju prečnika, orijentaciju vlakana, poroznost, dlakavost, površinsku hemiju i strukturnu složenost određenu primenom deskriptora zasnovanih na analizi slike, kao što su entropija, fraktalna dimenzija i teksturne karakteristike. U radu su dati pregled konvencionalnih deskriptora pređe, analiza savremenih metoda karakterizacije i njihov značaj za definisanje predloženog Genoma pređe. Na kraju su razmotrene buduće perspektive koje uključuju primenu veštačke inteligencije, digitalnih blizanaca, inteligentnih sistema predenja, standardizovanih baza podataka Genoma pređe i digitalnih pasoša tekstilnih proizvoda. Predloženi okvir predstavlja konceptualnu osnovu za novu generaciju karakterizacije pređe i pruža podršku razvoju prediktivnog tekstilnog inženjerstva, inteligentne kontrole kvaliteta i proizvodnje zasnovane na podacima.

Ključne reči: *Genom pređe; struktura pređe; strukturni deskriptori; digitalna analiza slike; karakterizacija tekstila; veštačka inteligencija; poroznost; orijentacija vlakana; dlakavost.*

1. INTRODUCTION

Yarn is the fundamental structural element of textile products, linking individual fibers to finished fabrics [1-3]. Its structure governs mechanical, physical, and functional properties, including strength, comfort, permeability, durability, and dyeability. Consequently, yarn characterization has long been a key research area in textile engineering. Conventional descriptors such as diameter, twist, linear density, evenness, hairiness, and tensile properties remain essential for quality assessment. However, each describes only one aspect of the complex hierarchical fiber assembly, highlighting the need for a more comprehensive structural characterization framework [4].

Yarn is a heterogeneous three-dimensional assembly of fibers with varying orientations, packing densities, porosity, and migration paths [5]. Consequently, yarns with identical conventional parameters may exhibit substantially different mechanical, transport, and functional properties, demonstrating that no single descriptor can adequately represent their structural complexity.

Yarn characterization has evolved from conventional measurements of count, twist, diameter, and tensile properties to advanced techniques including optical microscopy, digital image analysis, three-dimensional imaging, and artificial intelligence. This

progression has shifted textile research toward integrated, multidimensional structural characterization (Figure 1).

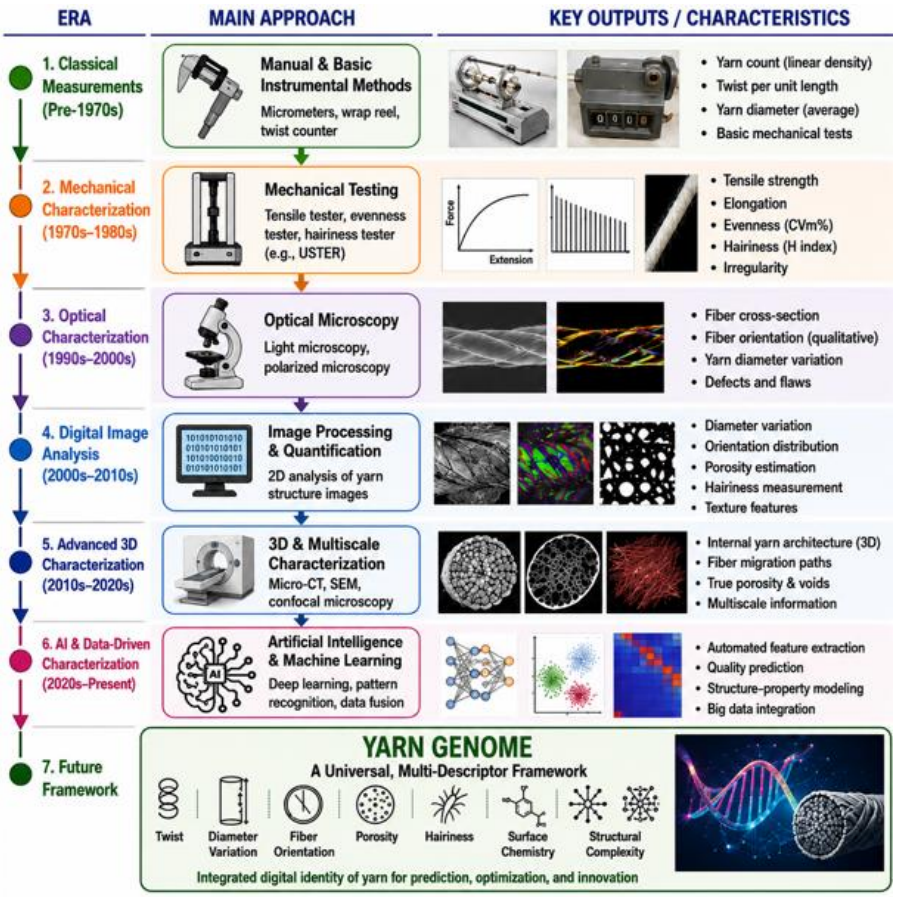

Figure 1: Evaluation of yarn characterization methods

Advances in digital imaging, computer vision, micro-CT, SEM, and artificial intelligence enable simultaneous extraction of structural descriptors such as fiber orientation, porosity, texture, and entropy, providing more comprehensive yarn characterization [6,7]. Nevertheless, current approaches remain fragmented, typically evaluating descriptors independently rather than as an integrated structural system.

Inspired by the Materials Genome Initiative (MGI), which integrates multidimensional descriptors to predict material performance [8], this review proposes the Yarn Genome—a universal framework combining conventional and image-derived structural descriptors to

establish a digital yarn identity for predictive modeling, intelligent quality assessment, digital twins, and AI-assisted textile engineering.
The objective of this review is therefore threefold: (i) to summarize conventional yarn structural descriptors and their limitations; (ii) to introduce the concept of a Yarn Genome as a comprehensive multidimensional framework for yarn characterization; and (iii) to discuss future opportunities for AI-driven textile engineering based on integrated structural descriptors.

2. CONVENTIONAL YARN STRUCTURAL DESCRIPTORS

Yarn structural characteristics govern both textile processing and final product performance. Conventional characterization relies on individual descriptors that quantify specific structural features and support quality control. However, these isolated measurements cannot fully represent the complex three-dimensional fiber organization, highlighting the need for integrated multidimensional structural characterization.
Yarn diameter is a fundamental geometric descriptor influencing fabric cover, mechanical properties, air permeability, thermal insulation, and dye penetration. It is commonly measured using optical microscopy, laser techniques, or image analysis. However, average diameter alone cannot adequately represent structural variability because yarn diameter fluctuates continuously due to irregular fiber arrangement and measurement conditions [9].
Twist, defined as the number of turns per unit length, is a key parameter controlling fiber cohesion, tensile strength, and yarn stability. Although higher twist improves fiber binding, excessive twist reduces softness and flexibility. Conventional measurements report only average twist, overlooking local variations and fiber migration that also influence yarn performance [9].
Hairiness describes fibers protruding from the yarn surface and influences abrasion resistance, pilling, friction, dye uptake, weaving performance, and fabric appearance. Commonly measured using optical or capacitive instruments, it characterizes only surface morphology and provides limited information about internal fiber arrangement and structural heterogeneity [10].
Yarn irregularity, commonly expressed as the coefficient of mass variation (CVm%), quantifies mass fluctuations along the yarn length. It influences tensile properties, dye uniformity, and fabric quality. Although modern evenness testers rapidly assess yarn uniformity, CVm% remains a statistical indicator and does not identify structural causes such as fiber migration, packing density, or diameter variation [11].
Fiber orientation describes the spatial arrangement of fibers within the yarn and strongly influences mechanical and transport properties. Although advanced techniques such as optical microscopy and micro-CT enable detailed visualization, quantitative evaluation remains challenging because fiber orientation continuously varies throughout the yarn structure [5].
Porosity governs transport properties within yarn and influences dyeing, finishing, filtration, and composite impregnation. Modern image analysis and micro-CT improve

pore characterization, but comprehensive evaluation requires integration with other structural descriptors within the proposed Yarn Genome framework [12].

3. TOWARD THE CONCEPT OF A YARN GENOME

Advances in imaging, computational modeling, and artificial intelligence have greatly enhanced yarn characterization by revealing structural features across multiple length scales. However, current approaches remain fragmented, lacking a unified framework to integrate diverse structural descriptors. A similar challenge was addressed by the Materials Genome Initiative (MGI), which introduced a descriptor-based approach combining experiments, simulations, and digital databases to enable data-driven prediction of material behavior and support digital twins, machine learning, and intelligent manufacturing systems (Figure 2) [8].

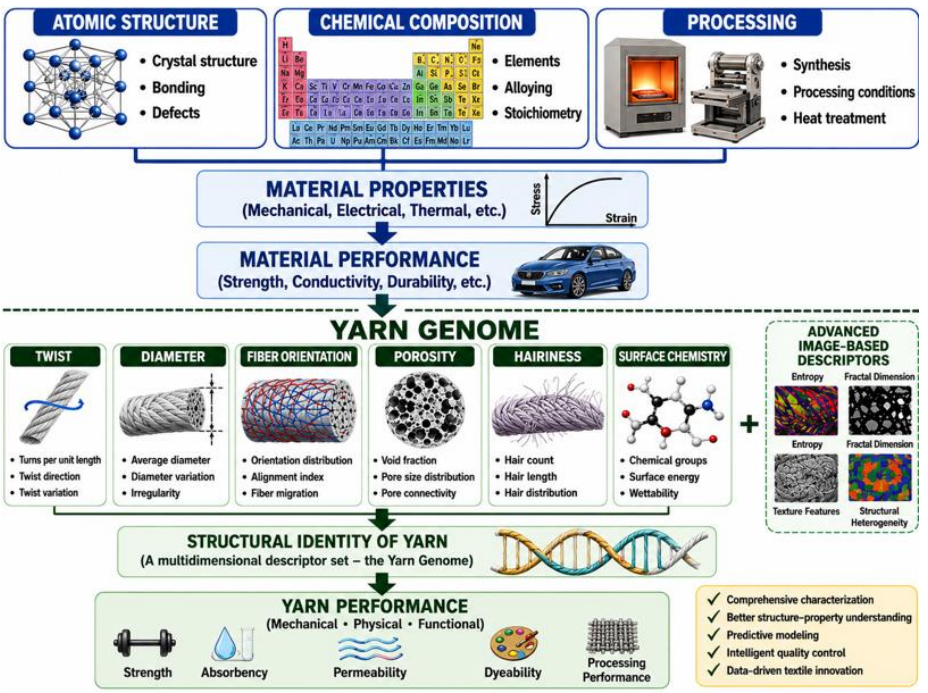

Figure 2: Analogy between the materials genome and the proposed Yarn Genome

The Materials Genome Initiative (MGI**)** demonstrated that complex materials require integrated descriptor sets rather than isolated parameters to accurately predict performance [8]. Similarly, textile yarns are hierarchical fibrous assemblies whose mechanical, physical, and functional properties arise from interactions among descriptors such as twist, diameter, fiber orientation, porosity, and hairiness rather than any single parameter [5]. While

conventional methods evaluate these descriptors individually, recent advances in digital image processing, micro-computed tomography, optical imaging, and artificial intelligence enable their simultaneous extraction, creating opportunities for integrated, descriptor-based yarn characterization.

4. COMPONENTS OF THE YARN GENOME

The proposed Yarn Genome integrates complementary structural descriptor groups into a unified framework that captures both external morphology and internal fiber organization. Inspired by the Materials Genome Initiative, it combines multiple measurable variables into a multidimensional structural fingerprint, providing a more comprehensive representation of yarn architecture than conventional individual descriptors.

Twist is a key structural parameter governing fiber cohesion and yarn stability. While conventional characterization reports average twist (TPM or TPI), it does not capture its spatial variability [9]. The proposed twist descriptor group includes twist level, angle, direction (S/Z), local variation, and distribution, collectively providing a more comprehensive description of fiber binding and its influence on yarn performance.

Yarn diameter is traditionally reported as an average value; however, it varies continuously because of drafting irregularities, fiber migration, and packing density variations [5,9]. The proposed diameter descriptor group includes average diameter, diameter variation, longitudinal profile, and diameter distribution, providing a more comprehensive characterization of structural uniformity, processing stability, and yarn geometry than a single average measurement.

Fiber orientation strongly influences yarn mechanical and transport properties [5]. The proposed fiber Orientation descriptor group includes orientation distribution, orientation tensor, alignment coefficient, fiber migration index, and orientation heterogeneity. Quantified using optical microscopy, digital image analysis, or micro-computed tomography, these descriptors comprehensively characterize the internal yarn architecture.

The porosity descriptor group characterizes the internal transport network using descriptors such as total porosity, pore-size distribution, pore connectivity, tortuosity, and spatial porosity distribution, which are essential for predicting dyeing, finishing, filtration, and composite impregnation.

The hairiness descriptor group extends conventional hairiness evaluation by incorporating hair length distribution, protruding fiber density, surface fiber orientation, spatial clustering, and surface roughness, providing a more comprehensive description of yarn surface morphology and its influence on friction, abrasion resistance, pilling, and fabric appearance.

The surface chemistry descriptor group complements structural characterization by describing functional properties through descriptors such as functional groups, surface energy, wettability, chemical composition, plasma or enzymatic modifications, and polymer or nanoparticle coatings [13-15]. These descriptors establish a direct relationship between yarn architecture and functional performance, including dyeability, adhesion, and antimicrobial activity.

The structural complexity descriptor group incorporates image-derived descriptors that quantify yarn heterogeneity beyond conventional measurements. It includes entropy, fractal dimension, GLCM texture features, Local Binary Patterns (LBP), Gabor features, and wavelet features [16]. Automatically extracted through digital image analysis, these descriptors characterize structural randomness, complexity, and spatial organization, making them particularly suitable for machine learning and artificial intelligence applications.

The proposed Yarn Genome comprises seven descriptor groups: twist, diameter, fiber orientation, porosity, hairiness, surface chemistry, and structural complexity. By integrating these complementary descriptors into a unified structural fingerprint, the Yarn Genome provides a comprehensive representation of yarn identity and establishes a foundation for predictive modeling, digital twins, intelligent quality control, and AI-assisted textile engineering.

5. MEASUREMENT TECHNOLOGIES FOR YARN GENOME CHARACTERIZATION

Successful implementation of the proposed Yarn Genome requires characterization techniques capable of quantifying both conventional and advanced structural descriptors. While traditional textile testing remains essential, advances in imaging and computational analysis enable comprehensive extraction of structural information, making the integration of multiple measurement techniques fundamental to Yarn Genome characterization.

Optical microscopy is widely used for yarn characterization because it is simple, non-destructive, and enables quantitative evaluation of diameter, hairiness, fiber distribution, orientation, and texture through digital image analysis. Scanning electron microscopy (SEM) complements optical microscopy by providing high-resolution visualization of surface morphology, fiber interactions, roughness, coatings, and chemical modifications, making it particularly valuable for characterizing the external architecture and surface chemistry of the proposed Yarn Genome [17].

Micro-computed tomography (micro-CT) enables non-destructive three-dimensional visualization of internal yarn architecture, including fiber orientation, migration, packing density, and pore connectivity, making it essential for defining Yarn Genome descriptors [18]. Digital image analysis automatically extracts quantitative features such as diameter profiles, hairiness, orientation, porosity, and texture from yarn images with high repeatability and efficiency [9,12]. Advanced image-processing algorithms, including segmentation, entropy analysis, Gray-Level Co-occurrence Matrix (GLCM) [19], Local Binary Patterns (LBP), Gabor filters, and wavelet transforms, further quantify structural complexity, spatial heterogeneity, and local organization, providing descriptors unavailable through conventional textile measurements and supporting AI-driven Yarn Genome characterization.

Artificial intelligence represents the next stage of yarn characterization by integrating multiple Yarn Genome descriptors to predict yarn quality, mechanical properties, spinning defects, and processing performance. Machine learning and deep learning enable

automated analysis of multidimensional image-derived data, supporting predictive models and autonomous manufacturing. Together with advanced imaging techniques, these technologies provide the experimental and computational foundation for the Yarn Genome, enabling comprehensive digital characterization and intelligent textile engineering.

6. FUTURE PERSPECTIVES AND RESEARCH CHALLENGES

The proposed Yarn Genome establishes a conceptual foundation for next-generation digital textile engineering. By integrating multidimensional structural descriptors with artificial intelligence and advanced computational methods, it supports the transition from conventional yarn characterization to predictive, data-driven systems aligned with Industry 4.0 manufacturing.

Artificial intelligence (AI) is expected to play a central role in implementing the yarn genome by integrating multiple structural descriptors to predict yarn quality, mechanical properties, and processing performance. Machine learning and deep learning, particularly convolutional neural networks (CNNs), enable automatic extraction of complex structural features from textile images, improving prediction accuracy, automating quality evaluation, and reducing inspection time. These capabilities position AI as a key technology for future intelligent textile manufacturing.

Digital twin technology enables virtual representations of physical systems by integrating experimental data, computational models, and operational information. Within the proposed framework, the Yarn Genome can serve as the structural foundation for digital yarn twins, enabling simulation of yarn behavior under different conditions, optimizing spinning parameters, accelerating yarn design, and reducing experimental effort and manufacturing costs.

Future smart spinning systems will combine real-time sensing, machine vision, and multi-response optimization to continuously monitor yarn genome descriptors [20]. This enables autonomous adjustment of spinning parameters, improving process stability, minimizing material waste, reducing production variability, and shifting quality control from post-production inspection to real-time optimization.

Standardized Yarn Genome databases integrating conventional, image-derived, processing, and performance data are essential for supporting artificial intelligence, reproducibility, and data sharing. Furthermore, incorporating the Yarn Genome into digital product passports, together with IoT and cloud-based manufacturing, could enable complete digital traceability and promote transparent, data-driven, and sustainable textile production.

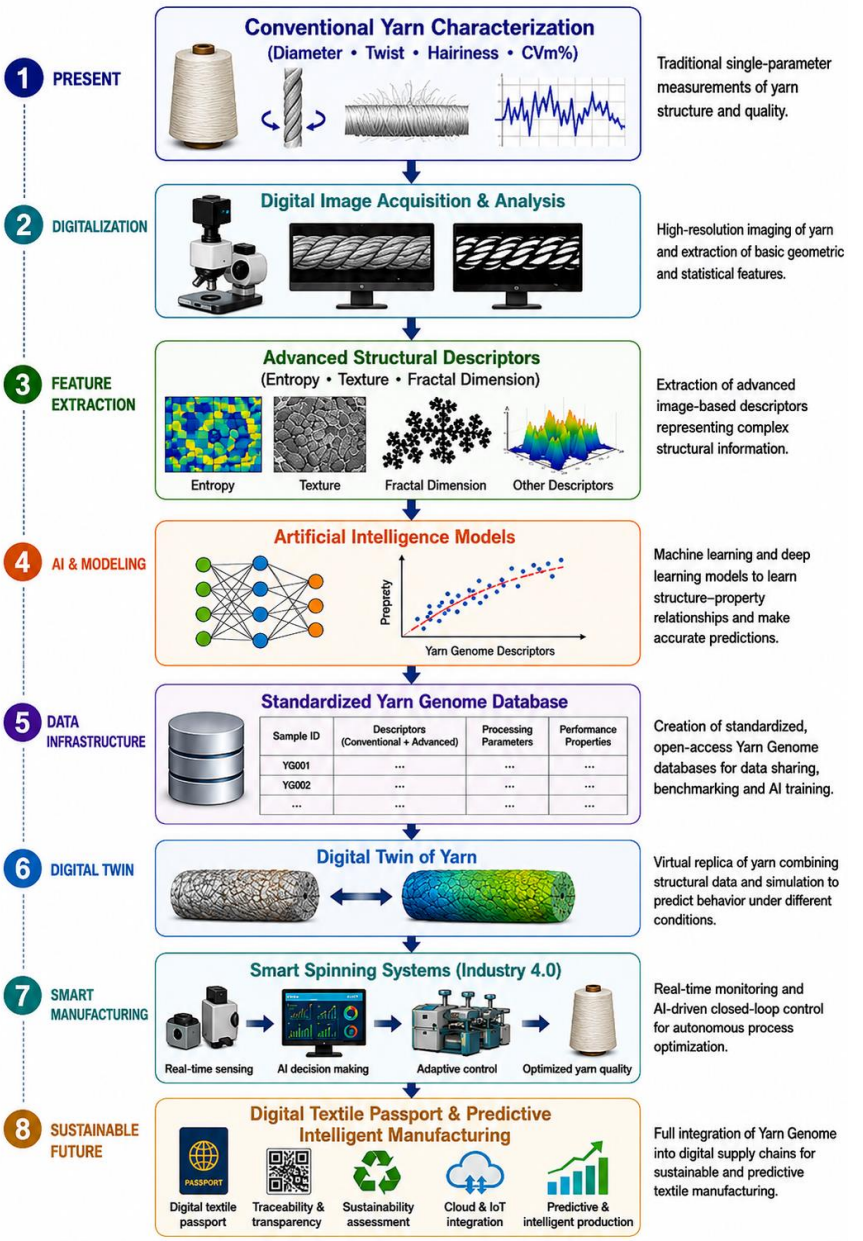

Figure 3: Future roadmap toward a universal Yarn Genome framework

7. CONCLUSION

Textile yarns are complex hierarchical structures whose behavior cannot be fully explained using isolated structural parameters. Conventional descriptors such as diameter, twist, hairiness, irregularity, fiber orientation, and porosity provide valuable information but describe only individual aspects of yarn architecture. This review introduced the Yarn Genome, a descriptor-based framework inspired by the Materials Genome Initiative that integrates conventional measurements with advanced image-derived descriptors, including entropy, fractal dimension, texture features, and surface chemistry, to establish a multidimensional representation of yarn identity. Advances in optical microscopy, SEM, micro-computed tomography, digital image analysis, and artificial intelligence provide the technological foundation for implementing this concept. Combined with machine learning, digital twins, standardized databases, and smart manufacturing, the Yarn Genome offers a promising framework for predictive textile engineering, intelligent quality control, and Industry 4.0. Future research should focus on descriptor standardization, large-scale Yarn Genome databases, and AI-driven prediction of yarn performance.

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FROM TEXTILE WASTE TO HIGH PERFORMANCE: A COMPARATIVE ANALYSIS OF REGENERATED CELLULOSE FIBERS IN WOVEN FABRICS

Scientific paper
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ABSTRACT: *The transition toward circular and sustainable textile systems has intensified the need for high-performance materials derived from post-consumer waste streams. In this context, regenerated cellulose fibers such as SaXcell™, produced from recycled cotton textiles, present a promising alternative to conventional and man-made cellulosic fibers. This study aims to systematically investigate the structure–property relationships of woven fabrics manufactured from lyocell fibers from textile wastes (SaXcell™ as brand name), lyocell fibers differing in cellulose sources (Tencel™ and Ecocell™ as brand names, respectively) and cotton fibers, with a particular focus on the influence of cotton/SaXcell™ blend ratios on overall fabric performance. Ring-spun yarns were produced from each fiber type and woven into plain weave fabrics under standardized conditions. The fabrics were characterized in terms of physical, mechanical, thermal and optical properties. All tests were conducted in accordance with relevant ISO standards. The findings reveal that fabrics produced from waste-derived regenerated lyocell fibers exhibited the highest weft-direction tensile strength and higher thermal absorptivity, which can be attributed to their fiber morphology and intermolecular structure. In terms of optical properties, the waste-derived regenerated lyocell fabric exhibited the highest whiteness index, whereas the conventional cotton fabric showed the highest lightness (L*) value after dyeing, demonstrating differences in optical behavior depending on fiber type and processing stage. The 50/50 cotton/SaXcell™ blend achieves a synergistic balance between mechanical durability, thermal comfort and aesthetic performance. Furthermore, all samples exhibited consistently high color fastness ratings, confirming the compatibility of regenerated fibers with conventional dyeing processes. Overall, this study provides a comprehensive comparative assessment of regenerated cellulose-based woven fabrics and*

highlights the potential of SaXcell™ as a viable and sustainable alternative in textile applications, offering critical insights into performance optimization and material selection for eco-efficient fabric design.

Keywords: *Sustainable textiles, circular economy, textile recycling, regenerated cellulose fibers, SaXcell™.*

OD TEKSTILNOG OTPADA DO VISOKIH PERFORMANSI: UPOREDNA ANALIZA TKANINA OD REGENERISANIH CELULOZNIH VLAKANA U TKANINAMA

APSTRAKT: *Prelazak na cirkularne i održive tekstilne sisteme intenzivirao je potrebu za visokoperformansnim materijalima dobijenim iz post-potrošačkih tokova otpada. U tom kontekstu, regenerisana celulozna vlakna kao što je SaXcell™, proizvedena od recikliranog pamučnog tekstila, predstavljaju obećavajuću alternativu konvencionalnim i veštačkim celuloznim vlaknima. Ova studija ima za cilj da sistematski istraži odnose strukture i svojstava tkanina proizvedenih od liocel vlakana iz tekstilnog otpada (SaXcell™ kao brend), liocel vlakana koja se razlikuju po izvorima celuloze (Tencel™ i Ecocell™ kao brendovi, respektivno) i pamučnih vlakana, sa posebnim fokusom na uticaj odnosa mešavine pamuk/SaXcell™ na ukupne performanse tkanine. Prstenasto ispredene pređe su proizvedene od svake vrste vlakana i tkane u tkanine platno prepletaja pod standardizovanim uslovima. Tkanine su okarakterisane u pogledu fizičkih, mehaničkih, termičkih i optičkih svojstava. Sva ispitivanja su sprovedena u skladu sa relevantnim ISO standardima. Rezultati pokazuju da tkanine proizvedene od regenerisanih liocel vlakana dobijenih iz otpada pokazuju najveću zateznu čvrstoću u pravcu potke i veću apsorpciju toplote, što se može pripisati njihovoj morfologiji vlakana i intermolekularnoj strukturi. Što se tiče optičkih svojstava, regenerisana liocel tkanina dobijena iz otpada pokazala je najviši indeks beline, dok je konvencionalna pamučna tkanina pokazala najveću vrednost beline (L*) nakon bojenja, što ukazuje na razlike u optičkom ponašanju u zavisnosti od vrste vlakana i faze obrade. Mešavina 50/50 pamuk/SaXcell™ postiže sinergističku ravnotežu između mehaničke izdržljivosti, termičke udobnosti i estetskih performansi. Štaviše, svi uzorci su pokazali konstantno visoke ocene postojanosti boje, potvrđujući kompatibilnost regenerisanih vlakana sa konvencionalnim procesima bojenja. Sve u svemu, ova studija pruža sveobuhvatnu uporednu procenu tkanina na bazi regenerisane celuloze i ističe potencijal SaXcell™ održive alternative u tekstilnim primenama, nudeći kritične uvide u optimizaciju performansi i izbor materijala za ekološki efikasan dizajn tkanina.*

Ključne reči: *Održivi tekstil, cirkularna ekonomija, reciklaža tekstila, regenerisana celulozna vlakna, SaXcell™.*

1. INTRODUCTION

The textile industry is facing increasing pressure to reduce its environmental footprint due to the intensive consumption of natural resources, high energy demand and the growing accumulation of textile waste. According to recent estimates, global textile fiber demand is expected to increase substantially in the coming decades, while the availability of conventional raw materials such as cotton remains limited. Consequently, the development of sustainable and circular material solutions has become a major research focus within the textile sector [1-4].

Among the various approaches proposed to support a circular textile economy, the recycling of post-consumer textile waste into high-value regenerated fibers has attracted considerable attention. Regenerated cellulosic fibers are regarded as promising alternatives to both conventional cotton and synthetic fibers due to their renewable origin, biodegradability and favorable textile performance characteristics [1,5]. In particular, lyocell fibers produced from regenerated cellulose have gained importance because of their excellent mechanical properties, moisture management behavior and environmental advantages compared with conventional fiber production systems [6].

Recent developments in chemical recycling technologies have enabled the recovery of cellulose from post-consumer cotton textiles and its conversion into regenerated fibers suitable for textile applications. These technologies provide an opportunity to retain the value of textile waste within the production cycle and reduce dependence on virgin raw materials. Life cycle assessment studies have demonstrated that regenerated cellulose obtained through closed-loop recycling processes may significantly reduce environmental impacts compared with conventional cellulose production routes [7]. Furthermore, studies have shown that regenerated fibers produced from cotton waste can achieve mechanical and textile performance comparable to commercially available regenerated cellulosic fibers [4, 8, 9].

Although numerous studies have investigated recycled cotton fibers, regenerated cellulose fibers and textile recycling technologies, existing research has primarily focused on fiber production processes, structural characteristics and general textile performance [1, 9, 10]. Comprehensive investigations evaluating the physical, mechanical, thermal, optical and moisture management properties of woven fabrics produced from regenerated lyocell fibers derived from textile waste remain limited. In particular, studies comparing waste-derived regenerated lyocell fibers with lyocell fibers originating from different cellulose sources and conventional cotton fibers under identical fabric construction conditions are still scarce.

Therefore, the present study aims to comparatively evaluate the performance characteristics of woven fabrics produced from regenerated lyocell fibers derived from post-consumer textile waste, lyocell fibers obtained from different cellulose sources and conventional cotton fibers. Particular attention is given to the influence of regenerated lyocell/cotton blend ratios on fabric performance. The fabrics were characterized in terms of optical, mechanical, thermal and moisture management properties using standardized test methods. By providing a comprehensive assessment of the structure–property

relationships of these fabrics, this study contributes to the understanding of the performance potential of recycled regenerated cellulose fibers and supports their utilization in sustainable and circular textile production systems.

2. EXPERIMENTAL

2.1. Materials

Textile (yarns and fabrics) samples produced from different cellulosic fiber types were investigated in this study. The selected materials included regenerated lyocell fibers obtained from post-consumer cotton textile waste (SaXcell™), lyocell fibers produced from different wood-based cellulose sources (Tencel™ and Ecocell™), conventional cotton fibers, a blend of cotton and regenerated lyocell fibers.

Ring yarns from Tencel™ (Yarn 1), Ecocell™ (Yarn 2), conventional cotton fibers (Yarn 3), a conventional cotton/SaXcell™ blend (Yarn 4), and SaXcell™ (Yarn 5) were used in the study. The yarns were produced using compact spinning technology with a yarn count of Ne 30 and a twist level of 765 T/m. Then, all yarn samples were utilized as weft yarns in the production of plain woven fabrics, whereas a 20-denier recycled polyester monofilament yarn was used as the warp yarn. The fabrics had a sett of 48 × 30 threads/cm (warp × weft) and an areal density of approximately 90 g/m². Following weaving, all samples were subjected to identical bleaching, dyeing and finishing processes.

The constructional parameters and material compositions of the investigated fabrics are presented in Table 1.

Table 1: Structural properties of the woven fabric samples

Sample Code	Fabric Composition (%)	Warp Yarn	Weft Yarn	Warp/Weft Densitiy	Weave Report
Fabric 1	85% Tencel™, 15% Recycled PES	20 Denier Recycled Polyester Monofilament	Yarn 1: 30 Ne Tencel™ Ring Yarn	48 warp/cm 30 weft/cm	Plain Weave
Fabric 2	85% Ecocell™, 15% Recycled PES		Yarn 2: 30 Ne Ecocell™ Ring Yarn		
Fabric 3	85% Cotton, 15% Recycled PES		Yarn 3: 30 Ne Cotton Ring Yarn		
Fabric 4	43% SaXcell™, 42% Cotton, 15% Recycled PES		Yarn 4: 30 Ne 50/50 SaXcell™/Cotton Ring Yarn		
Fabric 5	85% SaXcell™, 15% Recycled PES		Yarn 5: 30 Ne SaXcell™ Ring Yarn		

2.2. Method

The experimental methodology consisted of yarn characterization, fabric production and comprehensive performance evaluation of the woven fabrics.

The physical and mechanical properties of the compact-spun yarns were evaluated prior to fabric production. Yarn evenness properties, including mass variation (CVm%), thin places (-50%/km), thick places (+50%/km), neps (+200%/km), hairiness (H) and hairiness variation (sh), were measured using an Uster Tester 6-S (Switzerland) at a testing speed of

400 m/min and a test duration of 2.5 min. Yarn tensile strength (N) and elongation at break (%) were determined using an Uster Tensorapid (Switzerland) at a testing speed of 400 m/min and a gauge length of 500 mm. All measurements were performed in triplicate. Statistical analyses were performed using one-way ANOVA at a confidence level of 95%. Differences between means were considered statistically significant at $p < 0.05$.

The performance of the woven fabrics was evaluated through physical, mechanical, thermal, optical and moisture management characterization tests.

Optical properties were measured using a Datacolor SF600 Plus-CT spectrophotometer. Whiteness index (CIE and Berger), color coordinates (L*, a*, b*), color strength (K/S), chroma (C*) and hue angle (h°) values were determined to evaluate the optical behavior of the fabrics.

Color fastness properties were assessed according to internationally accepted standards. Washing fastness, water fastness, perspiration fastness and rubbing fastness tests were carried out according to ISO 105-C06, ISO 105-E01, ISO 105-E04 and ISO 105-X12, respectively.

Mechanical performance was evaluated through tensile strength, seam slippage and pilling resistance tests. Tensile strength was measured according to ISO 13934-2, seam slippage according to ISO 13936-2 and pilling resistance according to ISO 12945-2. Dimensional stability after laundering was determined according to ISO 6330. Fabric mass per unit area was also measured and recorded for each sample.

The morphological characteristics of the fibers were examined using a Hitachi TM3030 Plus Scanning Electron Microscope (SEM). SEM images were obtained to investigate fiber surface morphology, structural uniformity and possible differences arising from cellulose source and recycling route.

The hydrophilicity behavior of the fabrics was evaluated by the vertical wicking method according to DIN 53 924:1997. Fabric specimens measuring 2.5 cm × 20 cm were immersed to a depth of 10 mm in distilled water and loaded with a weight of 0.69 g. The capillary rise height was recorded after 2, 5, 10, 15, 20, 25 and 30 min.

Thermal comfort properties were measured using an Alambeta instrument. Thermal conductivity, thermal resistance, thermal absorptivity and thermal diffusivity values were determined to evaluate the heat transfer characteristics and thermo-physiological comfort behavior of the fabrics.

The experimental results were comparatively analyzed to determine the influence of cellulose source and fiber composition on the overall performance of the yarn and woven fabrics. Particular attention was given to evaluating the performance of waste-derived regenerated lyocell fibers and identifying sustainable alternatives for eco-efficient textile applications.

3. RESULTS AND DISCUSSION

3.1. Yarn Properties

The average yarn properties of the compact-spun yarns produced from different cellulosic fiber types are presented in Table 2.

Table 2: Average yarn properties

Yarn Code	CVm (%)	Thin Places (-50%/km)	Thick Places (+50%/km)	Neps (+200%/km)	Hairiness (H)	Hairiness Variation (sh)	Tensile Strength (N)	Elongation at Break (%)
Yarn 1	12.23	0.00	10.33	12.00	5.75	1.41	5.67	9.63
Yarn 2	11.40	0.00	6.00	9.33	6.80	1.70	4.70	7.80
Yarn 3	11.01	0.00	7.67	3.67	4.18	0.87	3.69	5.70
Yarn 4	12.76	52.33	23.27	26.67	4.01	1.03	4.09	7.09
Yarn 5	10.18	0.00	6.67	25.83	3.64	0.78	3.56	4.52

The yarn evenness results revealed that the raw material type significantly affected yarn quality. The lowest unevenness value was obtained for the yarn produced from regenerated lyocell fibers derived from post-consumer textile waste (Yarn 5) (10.18% CVm), indicating a highly homogeneous yarn structure. In contrast, the regenerated lyocell/cotton blended yarn (Yarn 4) exhibited the highest unevenness value (12.76% CVm), which may be attributed to differences in fiber morphology and physical characteristics between the two fiber types. Statistical analysis confirmed that the effect of raw material on yarn unevenness was significant ($p < 0.05$). Hairiness results also showed a significant dependence on fiber type. The lowest hairiness value was observed for the yarn produced from waste-derived regenerated lyocell fibers (Yarn 5) (H = 3.64), followed by the regenerated lyocell/cotton blend (Yarn 4) (H = 4.01). In contrast, the highest hairiness value was obtained for one of the wood-based regenerated lyocell yarns (Yarn 2) (H = 6.80). Lower hairiness values are generally associated with improved yarn compactness and reduced fiber protrusion from the yarn surface. Statistical analysis indicated significant differences among the yarn types ($p < 0.05$). The tensile strength results demonstrated clear differences among the investigated yarns. The highest tensile strength was obtained for the wood-based regenerated lyocell yarn (Yarn 1) (5.67 N), followed by the second wood-based regenerated lyocell yarn (Yarn 2) (4.70 N). The yarn produced from waste-derived regenerated lyocell fibers (Yarn 5) exhibited a tensile strength of 3.56 N, which was statistically comparable to that of conventional cotton yarns (Yarn 3) (3.69 N). Interestingly, blending regenerated lyocell fibers with cotton improved tensile strength to 4.09 N, indicating a positive contribution of cotton fibers to yarn cohesion and load-bearing capacity. The elongation results followed a trend similar to tensile strength. The highest elongation at break was observed for the wood-based regenerated lyocell yarn (Yarn 1) (9.63%), while the waste-derived regenerated lyocell yarn exhibited the lowest elongation value (Yarn 5) (4.52%). The regenerated lyocell/cotton blend (Yarn 4) exhibited an elongation at break of 7.09%, which was higher than those of both the conventional cotton yarn (Yarn 3, 5.70%) and the pure waste-derived regenerated lyocell yarn (Yarn 5, 4.52%), but lower than those of the wood-based regenerated lyocell yarns (Yarn 1, 9.63% and Yarn 2, 7.80%).

These findings suggest that blending may provide a favorable balance between strength and extensibility. Overall, the yarn characterization results indicate that regenerated lyocell fibers obtained from post-consumer textile waste can be successfully processed on

conventional compact spinning systems and produce yarns with acceptable quality characteristics. Furthermore, blending recycled regenerated fibers with cotton appears to improve certain mechanical properties while maintaining low hairiness and satisfactory yarn uniformity.

3.2. Fiber and Fabric Morphology

SEM images of the woven fabrics at different magnifications are presented in Fig 1. All samples exhibited a regular plain weave structure without visible structural defects. At higher magnifications, the fabrics produced from regenerated lyocell fibers showed smoother and more uniform fiber surfaces compared to the conventional cotton fabric. The fabric produced from regenerated lyocell fibers derived from post-consumer textile waste (Fabric 5) exhibited a morphology comparable to those of the wood-based lyocell fabrics (Fabrics 1 and 2), indicating that the recycling process did not adversely affect fiber structure. The blended fabric (Fabric 4) displayed intermediate morphological characteristics between cotton and regenerated lyocell fibers. The smooth and homogeneous fiber surfaces observed for the regenerated lyocell fabrics are consistent with the lower yarn hairiness and improved yarn uniformity results obtained in this study (Tab 2).

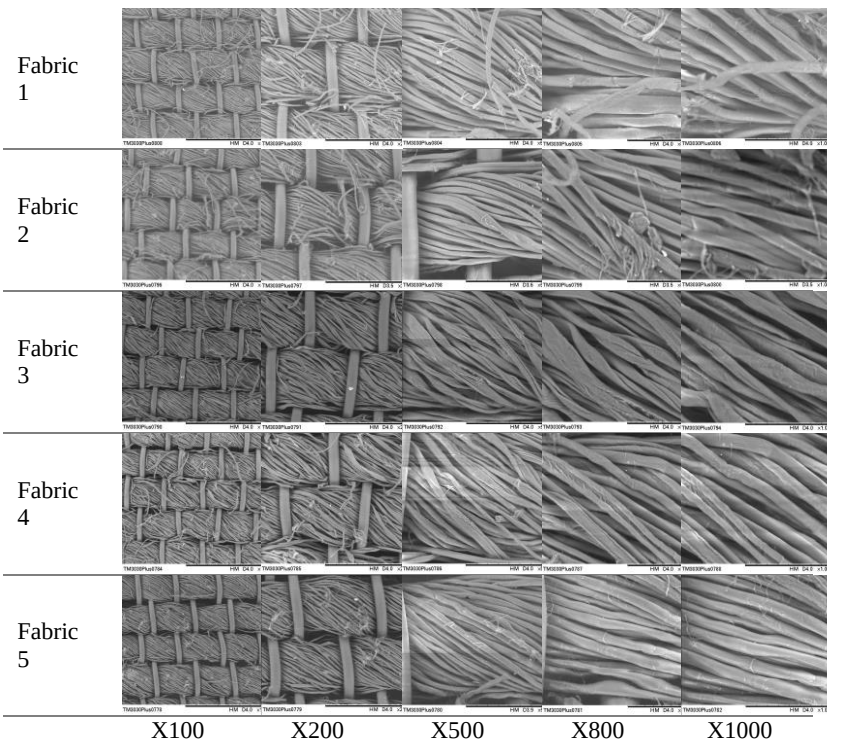

Figure 1: SEM micrographs of woven fabrics produced from different cellulose sources at magnifications of ×100, ×200, ×500, ×800 and ×1000.

Overall, the SEM observations confirm the suitability of recycled regenerated cellulose fibers for high-performance woven textile applications.

3.3. Optical Properties and Color Performance

The whiteness measurements of the greige fabrics revealed significant differences among the investigated cellulosic fiber types. As shown in Table 3, the regenerated lyocell fiber obtained from textile waste (Fabric 5) exhibited the highest Berger whiteness value (28.19) and CIE whiteness index (19.64), whereas conventional cotton fabrics (Fabric 3) showed the lowest whiteness values.

Table 3: Whiteness properties of greige fabrics

Sample Code	Berger Whiteness	CIE Whiteness
Fabric 1	24.02	14.20
Fabric 2	25.03	15.37
Fabric 3	21.99	10.56
Fabric 4	23.04	11.96
Fabric 5	28.19	19.64

The higher whiteness values obtained for Fabric 5 may be attributed to the purification and dissolution stages involved in the chemical recycling process, resulting in a more homogeneous cellulose structure. Similar observations have been reported for regenerated cellulose fibers derived from textile waste.

In Table 4, color measurements performed after dyeing showed that cotton fabrics exhibited the highest lightness value (L*=63.47), while regenerated fiber fabrics produced darker shades under identical dyeing conditions. The cotton/regenerated cellulose fibers derived from textile waste blend displayed intermediate color characteristics between pure cotton and pure regenerated fiber fabrics.

The color strength (K/S) results demonstrated that the highest color strength value was obtained for the fabric produced from wood-based regenerated lyocell fibers (K/S = 1.63), followed by the fabric produced from another wood-based regenerated lyocell fiber type (K/S = 1.52) and the fabric produced from regenerated lyocell fibers derived from post-consumer textile waste (K/S = 1.45). On the other hand, blending conventional cotton fibers with regenerated lyocell fibers derived from post-consumer textile waste increased the K/S value from 0.90 to 1.11, indicating improved color yield and dyeability compared with the 100% cotton fabric.

Table 4: CIELAB color coordinates and color strength (K/S) values of samples

Sample Code	L*	a*	b*	C*	h°	K/S
Fabric 1	57.28	4.27	7.67	8.78	60.90	1.52
Fabric 2	56.37	4.22	7.28	8.41	59.88	1.63

Sample Code	L*	a*	b*	C*	h°	K/S
Fabric 3	63.47	6.57	5.92	8.84	42.00	0.90
Fabric 4	60.71	5.28	5.84	7.87	47.87	1.11
Fabric 5	57.69	4.07	7.33	8.39	60.96	1.45

As shown in Figure 2, the waste-derived regenerated lyocell fabric exhibited the highest whiteness index among the investigated samples, while the conventional cotton fabric showed the lowest value. The lyocell fibers originating from wood-based cellulose sources achieved the highest color strength values, indicating superior dye uptake under identical dyeing conditions. The waste-derived regenerated lyocell fabric demonstrated color yield values comparable to those of the wood-based lyocell fabrics, confirming its suitability for conventional coloration processes. These results suggest that the cellulose source influences both optical appearance and dyeability; however, regenerated cellulose fibers generally exhibit superior color performance compared to conventional cotton fibers.

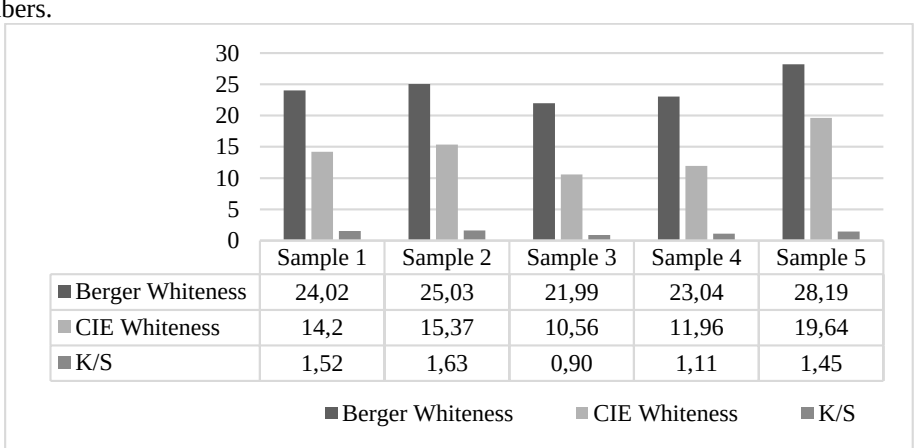

Figure 2: Comparison of CIE whiteness index and color strength (K/S) values of samples

3.4. Color Fastness Properties

The color fastness performance of the dyed woven fabrics was evaluated in terms of washing, water, acidic perspiration, alkaline perspiration and rubbing fastness according to the relevant ISO standards. The results are summarized in Table 5.

Table 5: Color fastness properties of the samples

Sample Code	Washing Fastness	Water Fastness	Acid Perspiration Fastness	Alkaline Perspiration Fastness	Dry Rubbing Fastness	Wet Rubbing Fastness
Fabric 1	4–5	4–5	4–5	4–5	4–5	4–5
Fabric 2	4–5	4–5	4–5	4–5	4–5	4–5
Fabric 3	4–5	4–5	4–5	4–5	4–5	4–5
Fabric 4	4–5	4–5	4–5	4–5	4–5	4–5
Fabric 5	4–5	4–5	4–5	4–5	4–5	4–5

As shown in Table 5, all investigated fabrics exhibited excellent color fastness performance. Washing, water, acidic perspiration, alkaline perspiration and rubbing fastness ratings were consistently evaluated as 4–5 for all samples, regardless of fiber type or cellulose source.

The results indicate that fabrics produced from waste-derived regenerated lyocell fibers, wood-based lyocell fibers and conventional cotton fibers can be successfully dyed using conventional coloration processes without compromising fastness performance. No significant differences were observed among the samples in terms of staining or color change behavior after washing, water exposure, perspiration or rubbing tests.

3.5. Physical and Mechanical Properties

The physical and mechanical test results are presented in Table 6. All fabrics exhibited good dimensional stability after laundering, with shrinkage values generally below 2%, indicating satisfactory dimensional performance regardless of fiber composition.

Pilling resistance ratings ranged between 4 and 5, indicating excellent surface durability for all samples.

The tensile strength results showed notable differences among fiber types. The highest weft-direction tensile strength was observed for the fabric produced from regenerated lyocell fibers derived from post-consumer textile waste (215.07 N), followed by conventional cotton fabric (199.74 N), fabrics produced from wood-based lyocell fibers (194.22 N and 186.72 N, respectively). These results suggest that the regenerated cellulose fiber derived from textile waste possesses a highly efficient load-bearing structure. The relatively low weft-direction tensile strength of the blended fabric may be attributed to the interaction of fibers with different morphological and mechanical characteristics within the yarn structure.

In the warp direction, cotton fabrics exhibited the highest tensile strength (229.86 N), while the fabric produced from the cotton/regenerated lyocell blend showed the second highest value (213.48 N). The blend fabric demonstrated a balanced performance in both directions, indicating a synergistic interaction between cotton and regenerated cellulose fibers derived from textile waste.

Table 6: Mechanical properties of fabrics

Sample Code	Tensile Strength Weft (N)	Tensile Strength Warp (N)	Seam Slippage Warp (mm)	Seam Slippage Weft (mm)
Fabric 1	186.72	164.93	3.45	4.44
Fabric 2	194.22	197.54	3.12	3.46
Fabric 3	199.74	229.86	3.14	3.29
Fabric 4	108.28	213.48	3.24	4.51
Fabric 5	215.07	200.92	3.16	3.51

3.6. Thermal and Hydrophilicity Properties

As presented in Table 7, the thermal comfort properties of the investigated fabrics were significantly influenced by fiber composition and cellulose source. Among the tested samples, the conventional cotton fabric exhibited the highest thermal conductivity value (19.47×10^{-3} W/mK), whereas fabrics produced from regenerated cellulose fibers generally showed lower thermal conductivity values. However, the differences between the samples were relatively small, indicating comparable heat transfer characteristics.

The most notable variation was observed in thermal absorptivity. According to Table 7, the fabric produced from regenerated lyocell fibers derived from post-consumer textile waste exhibited the highest thermal absorptivity value (251.97 $Ws^{1/2}/m^2K$), followed by the regenerated lyocell/cotton blend (234.13 $Ws^{1/2}/m^2K$). Since higher thermal absorptivity values are associated with a cooler sensation during initial skin contact, these fabrics are expected to provide enhanced thermo-physiological comfort, particularly in warm-weather clothing applications. The results therefore suggest that waste-derived regenerated lyocell fibers can contribute positively to the development of sustainable fabrics with improved cooling performance.

Table 7: Thermal properties of samples

Sample Code	Thermal Conductivity ($\times 10^{-3}$ W/mK)	Thermal Diffusivity ($\times 10^{-6}$ m^2/s)	Thermal Absorptivity ($Ws^{1/2}/m^2K$)	Thermal Resistance ($\times 10^{-3}$ Km^2/W)	Heat Flow Density (W/m^2)
Fabric 1	18.60	0.00767	212.60	11.97	436.40
Fabric 2	18.70	0.00800	213.47	12.10	437.27
Fabric 3	19.47	0.00800	222.97	11.53	440.27
Fabric 4	18.80	0.00667	234.13	11.57	439.40
Fabric 5	18.47	0.00533	251.97	11.20	462.03

The hydrophilicity performance of the woven fabrics was evaluated using the vertical wicking method and the results are presented in Figure 3. The wicking height increased with increasing test duration for all samples, indicating continuous capillary water transport through the fabric structure.

As shown in Figure 3, the fabric produced from conventional cotton fibers exhibited the highest wicking performance throughout the entire test period. After 30 minutes, the cotton fabric reached a wicking height of 8.30 cm, demonstrating its superior moisture transport capability. This behavior can be attributed to the natural hydrophilic structure of cotton fibers and their ability to rapidly absorb and transport liquid water through capillary action. The fabric produced from the blend of regenerated lyocell fibers derived from post-consumer textile waste and cotton fibers exhibited the second-highest wicking performance, reaching a height of 7.40 cm after 30 minutes. The improved liquid transport behavior of the blended fabric suggests that the incorporation of cotton fibers positively contributes to moisture movement within the fabric structure.

The fabrics produced from lyocell fibers originating from different cellulose sources exhibited similar wicking characteristics, with final wicking heights ranging between 6.53 and 6.90 cm after 30 minutes. Among these samples, the fabric produced from wood-based regenerated lyocell fibers showed slightly higher liquid transport performance than the fabrics produced from waste-derived regenerated lyocell fibers. However, the differences were relatively small, indicating comparable hydrophilic behavior.

The average wicking heights calculated over the entire test period were 6.62 cm for conventional cotton, 5.99 cm for the regenerated lyocell/cotton blend, 5.62 cm and 5.37 cm for the wood-based regenerated lyocell fabrics and 5.26 cm for the waste-derived regenerated lyocell fabric. These results indicate that although the conventional cotton fabric exhibited the highest wicking performance, all regenerated lyocell fabrics reached wicking heights exceeding 6.5 cm after 30 min, indicating effective moisture transport behavior.

	2 min	5 min	10 min	15 min	20 min	25 min	30 min	Mean
Sample 1	3,37	4,40	5,57	6,10	6,37	6,60	6,90	5,62
Sample 2	3,30	4,33	5,27	5,80	6,00	6,33	6,53	5,37
Sample 3	3,87	5,10	6,37	7,13	7,57	8,03	8,30	6,62
Sample 4	3,70	4,63	5,73	6,47	6,90	7,13	7,40	5,99
Sample 5	3,07	4,20	5,03	5,57	6,03	6,37	6,53	5,26

Sample 1 Sample 2 Sample 3
Sample 4 Sample 5

Figure 3: Vertical wicking height versus time for samples

4. CONCLUSION

This study presented a comprehensive comparison of woven fabrics produced from conventional cotton fibers, wood-based regenerated lyocell fibers and regenerated lyocell fibers derived from post-consumer textile waste. The results demonstrated that the source

of cellulose significantly influences the optical, mechanical, thermal and moisture management performance of woven fabrics.

The fabrics produced from regenerated lyocell fibers obtained through textile waste recycling exhibited performance characteristics comparable to, and in some cases superior to, those of conventional cotton and wood-based regenerated lyocell fibers. In particular, the waste-derived regenerated lyocell fabric showed the highest weft-direction tensile strength and thermal absorptivity values among the investigated samples. These results indicate that the chemical recycling process can generate regenerated cellulose fibers with excellent structural integrity and favorable thermo-physiological comfort properties.

The color measurement results further revealed that regenerated lyocell fibers exhibited high dye affinity and color yield, while all samples demonstrated excellent washing, water, perspiration and rubbing fastness properties. This confirms that recycled regenerated cellulose fibers can be successfully integrated into existing dyeing and finishing processes without compromising product quality.

Although conventional cotton fabrics exhibited the highest moisture transport performance, fabrics containing regenerated lyocell fibers also provided satisfactory hydrophilicity characteristics. Furthermore, the cotton/regenerated lyocell blend displayed a balanced combination of tensile performance, thermal comfort, moisture management and color properties, demonstrating the potential benefits of blending recycled regenerated fibers with conventional natural fibers.

SEM observations revealed that the regenerated lyocell fibers derived from textile waste possessed a smooth and homogeneous surface morphology comparable to that of commercially available regenerated cellulose fibers. These morphological characteristics were found to be consistent with the favorable yarn quality, mechanical performance and comfort-related properties obtained throughout the study.

Overall, the morphological, mechanical and thermal performance results collectively demonstrate that regenerated lyocell fibers derived from textile waste can achieve performance levels comparable to commercially available regenerated cellulose fibers, supporting their potential for large-scale industrial implementation. The findings confirm that regenerated lyocell fibers produced from post-consumer textile waste represent a viable and sustainable alternative to conventional and wood-based cellulosic fibers. The high performance achieved by the recycled regenerated fibers highlights their potential for high-value textile applications while supporting circular economy principles, reducing textile waste and contributing to more resource-efficient and environmentally responsible textile production systems.

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EFFECTS OF WASHING ON BENDING PROPERTIES OF COTTON MILANO RIB FABRIC

Scientific paper
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ABSTRACT: *This study investigates the effects of washing on the bending properties of cotton Milano rib fabric, along with associated dimensional and structural changes. The results showed that washing causes ~5.4% shrinkage in both directions, increases stitch density, while stitch length remains unchanged. Fabric mass and thickness increase, resulting in a denser structure. The bending properties showed that the fabric exhibits statistically increased drape coefficient, with a higher number of nodes, as well as higher bending stiffness in both directions, despite a decrease in bending modulus. These results demonstrate the complex impact of washing on the structural and mechanical performance of knitted fabric.*

Keywords: *cotton Milano rib, washing, drape coefficient, bending stiffness, bending modulus.*

UTICAJ PRANJA NA SVOJSTAVA SAVIJANJA PAMUČNE MILANO REBRASTE PLETENINE

APSTRAKT: *Ova studija ispituje uticaj pranja na svojstva savijanja pamučne Milano rebraste pletenine, zajedno sa povezanim dimenzionalnim i strukturnim promenama. Dobijeni rezultati su pokazali da pranje uzrokuje skupljanje od ~5.4% u oba pravca, povećava gustinu pletenine, dok dužina pređe u petlji ostaje nepromenjena. Masa i debljina pletenine se povećava, što rezultira gušćom strukturom. Rezultati svojstava savijanja pletenina nakon pranja pokazali su statistički značajano povećanje koeficijenta drapiranja, sa većim brojem nabora, kao i veću krutost savijanja u oba pravca, uprkos smanjenju modula savijanja. Ovi rezultati pokazuju složen uticaj pranja na strukturne i mehaničke performanse pletenine.*

Ključne reči: *pamučna Milano rebrasta pletenina, pranje, koeficijent drapiranja, krutost savijanja, moduo savijanja.*

1. INTRODUCTION

Knitted fabrics are highly valued for their comfort, stretchability, and versatility, making them ideal for a wide range of clothing and technical applications [1]. Their performance is primarily governed by the interaction between knit structure and yarn properties, with structural variations playing a key role in determining mechanical and functional behavior [2]. Through appropriate knit structures, it is possible to enhance dimensional stability, mechanical performance, and aesthetic qualities.

Garment appearance and fit depend on both mechanical properties (tensile, bending, and shear) and structural characteristics such as mass per unit area, thickness, and stitch density [3], [4]. Among these, bending behavior is particularly significant, as it directly influences fabric flexibility, drape, and overall performance [5]. It is affected by multiple factors, including fiber composition, yarn characteristics, fabric density, knit structure, and finishing treatments [6][8].

Bending stiffness is a key parameter governing drape behavior: fabrics with low stiffness exhibit smooth, fluid drape, whereas stiffer fabrics form more defined, structured folds. Since drape reflects the mechanical response of a fabric to its own weight, bending properties play a dominant role in determining the garment’s appearance. Previous studies confirm that knit structure significantly affects bending behavior, with more open structures generally exhibiting greater flexibility than compact configurations [9], [10].

In this context, the bending stiffness of 1×1 rib and half Milano rib fabrics, produced from various cotton/PET blends, is strongly influenced by fabric structure, direction, and finishing [11]. Stiffness is consistently lower in the course direction than in the wale direction, and higher on the technical face than on the back side, reflecting the anisotropic nature of knitted fabrics. The 1×1 rib fabrics exhibit lower bending stiffness compared to the half Milano rib fabrics due to their more open and elastic loop configuration. Furthermore, all applied treatments (dying, softening with Aquasoft® SI hydrophilic softener, and Polygiene VO-600 antibacterial finish) reduce bending stiffness relative to untreated fabrics, indicating improved flexibility and enhanced fabric handle.

The purpose of this investigation is to evaluate the effect of washing on the bending behaviour of cotton Milano rib knitted fabric, together with the associated dimensional and structural changes, in order to better understand how washing influences fabric stability, density, and mechanical performance.

2. MATERIALS AND METHODS

2.1. Materials

In this study, knitted fabric was produced using a commercially available cotton yarn (19 × 2 tex). The yarn exhibited an experimentally determined linear density of 37.8 ± 0.4 tex, a twist of 266 ± 20 turns/m, a breaking force of 516 ± 35 cN, a tenacity of 13.65 cN/tex, and a breaking elongation of 3.6 ± 0.6% [12].

Knitting was performed on a CMS 340.6L double-needle flat V-bed knitting machine (Stoll, Germany), E12 gauge, with 863 needles per needle bed and four knitting systems.

To ensure consistent fabric quality, all relevant machine settings – such as stitch cam position, yarn feeding tension, and take-down adjustments – were maintained unchanged throughout the process. For this study, the Milano rib structure (Figure 1) was chosen.

(a) (b) (c)

Figure 1: Milano rib structure: a) graphical notation, photos b) before washing, and c) after washing with a measuring ruler (X-axis in mm, Y-axis in inches)

The Milano rib knit structure is produced using three cam systems (Figure 1a). In the first system, knit loops are formed on needles of both needle beds (1x1 rib), while in the second system, knit loops are created only on the needles of the back needle bed (plain), and in the third system, the knit loops are formed on the needles of the front needle bed (plain). As a result, the technical face and back of the fabric are identical (Figures 1b and 1c). Two courses on the face correspond to two courses on the back.

2.2. Methods

Determination of the dimensional changes of the knitted fabric caused by washing

The dimensional changes (*DC*, %) of the knitted fabric after a one washing cycle were assessed by calculating the percentage variation in the wale and course directions. After knitting, the samples were conditioned by laying them flat for several days under standard atmospheric conditions to relax residual stresses induced during knitting. Following this dry relaxation period (dry relaxed state – *DR*), the samples were washed in accordance with ISO 6330:2023. After washing, the fabric was again laid flat under minimal tension and conditioned for at least 24 hours under standard atmospheric conditions (wash or wet relaxed state – *WR*). The mean percentage of dimensional change – expressed as shrinkage („–“) or expansion („+“) – in both the wale and course directions was then calculated using the methodology described in the litarature [12].

Determination of the structural characteristics of the knitted fabric

The structural characteristics of the knitted fabric, before and after washing, were evaluated by determining the number of wales (*WPC*, loops/cm), the number of courses (*CPC*, loops/cm) per centimeter, and fabric stitch density (*S*, loops/cm^2). Furthermore, stitch length was measured for the 1x1 rib stitches (l_1, mm), plain stitches (l_2, mm), and expressed as the average stitch length (l_a, mm). The fabric mass per unit area or weight (*W*, g/m^2) and thickness (*T*, mm) were also determined. The structural characteristics of the cotton Milano

rib fabric were determined in accordance with the methodology described in the literature [12].

Determination of the bending properties of the knitted fabric

The bending properties of cotton Milano rib knitted fabric were evaluated using the drape coefficient, number of nodes, bending stiffness, and bending modulus before and after washing.

The disc method was used to determine the drape coefficient (K_d, %) using an apparatus designed at the Department of Textile Engineering, Faculty of Technology and Metallurgy, University of Belgrade. In the test, a circular sample of knitted fabric (with a diameter (D) of 20 cm) is held concentrically between two smaller horizontal discs (with a diameter (d) of 8 cm) and is allowed to drape into nodes under its own weight. A light is shone from underneath the specimen, and the shadow that the fabric casts is traced onto a piece of paper the same size as the undeformed fabric specimen. To measure the areas involved, the mass of a paper disk whose dimensions are equal to the dimensions of the undeformed sample (m_{A_D}, g), the mass of a paper disk whose dimensions are equal to the dimensions of the horizontal discs(m_{A_d}, g), and the mass of paper corresponding to the area of the sample projected shadow (m_{A_s}, g) are cut away and weighed [13]-[15]. The drape coefficient (K_d, %), which characterizes the drapeability of the investigated knitted fabric in all structural directions, is calculated according to the following equation:

$$K_d = \frac{m_{A_s} - m_{A_d}}{m_{A_D} - m_{A_d}} \cdot 100 \quad (1)$$

The drape coefficient is the mean value of six measurements.

The cantilever method [13], [16] was used to determine the bending stiffness and bending modulus of the investigated knitted fabric. The method consisted of fixing a tested specimen measuring 16 x 3 cm at its central part, so that it would fall freely to both sides under the influence of its own weight. The magnitude of the absolute deflection (f) was read separately for each free end of the fabric, and then the bending of the tape (f_{sr}) was determined as the arithmetic mean value of the deflection of both ends (f_1) and (f_2). The relative deflection (f_o) was calculated by the equation $f_o=f_{sr}/l$, where l is the length of the hanging-down ends of the test stripe (cm), determined by the equation:

$$l = \frac{L-2}{2} \quad (2)$$

where L is the length of the test stripe (in this case, it is 16 cm).

The size of relative deflection (f_o) is not allowed to be greater than 0.65, and the size of average deflection (f_{sr}) is not less than 1 cm. If at 16 cm long test stripe these conditions are not satisfied, the length of the stripe is reduced by 1 cm and relative as well as average deflection are determined again. The procedure of reducing the length of the test stripe is repeated as long as it is needed to obtain the values of (f_o) and (f_{sr}), which will satisfy the mentioned limited conditions.

Bending stiffness (B, N·m^2) was calculated according to the equation:

$$B = \frac{m \cdot l^3}{A} \tag{3}$$

where m is the weight per unit length (N·m^{-1}) of the test stripe, l is the hanging length (m) of the test stripe, which was determined according to equation (2), and A is the dimensionless value, in dependence on relative deflection (f_o) given in the literature [13], [16].
Bending modulus (E, N·m^{-2}) was calculated through the value of bending stiffness (B) using the equation [13]:

$$E = \frac{B}{I_x} \tag{4}$$

where B is the bending stiffness (N·m^2), which was determined according to equation (3), and I_x (m^4) is the principal moment of inertia given by the following equation [13]:

$$I_x = \frac{b \cdot T^3}{12} \tag{5}$$

where b is the sample width (3 cm, i.e., 0.03 m), and T is the fabric thickness (m) determined under the pressure of 9.96 kPa. The results for bending stiffness and bending modulus presented a mean of five measurements of knitted fabric in both directions (in the wale and course directions).

Statistical analysis
The statistical analysis used the Student t-test [17] for the dependent samples, which was calculated using the equation:

$$t = \frac{\bar{d}}{\frac{\sigma_d}{\sqrt{n}}} \tag{6}$$

where $\bar{d}$ is the sample mean value of the differences of determining characteristic before and after washing, σ_d is the sample standard deviation of the differences, while n is the sample size.

3. RESULTS AND DISCUSSION

3.1. Dimensional changes of the knitted fabric

As mentioned in the Methods section, the dimensional changes were measured after one washing cycle in both directions (wale and course), and the results are presented in Tab 1. The analyzed dimensional changes of the cotton Milano rib fabric after washing show shrinkage in both the wale and course directions, indicating isotropic dimensional behavior as previously reported [12]. The shrinkage of Milano rib fabric in both the wale and course directions is similar (5.28% and 5.61%, respectively) due to the structure of the Milano rib,

which features courses of plain stitches created on the opposite needle bed by the second and third systems of the knitting machine. However, the variability in dimensional change is notably large in both directions, as reflected by large coefficients of variation. This indicates non-uniform shrinkage behavior, with slightly greater dispersion observed in the wale direction. Overall, although shrinkage occurs in both directions with similar mean values, the fabric demonstrates inconsistent dimensional stability, particularly in the wale direction.

Table 1: Final measurements (*FM*) and shrinkage (*DC*) of the Milano rib fabric after washing

Parameter	In the wale direction			In the course direction		
	mean	*SD*	*CV*, %	mean	*SD*	*CV*, %
FM, mm	189.44	5.13	2.71	188.78	4.71	2.50
DC, %	5.28	2.56	48.56	5.61	2.36	41.98
FM – final measurement, *DC* - shrinkage, *SD* – standard deviation, *CV* – coefficient of variation						

3.2. Structural characteristics of the knitted fabric

Structural characteristics of the Milano rib structure in dry relaxed (*DR*) and washed (*WR*) states are presented in Table 2.

Table 2: Structural characteristics of the Milano rib structure in dry relaxed (*DR*) and washed (*WR*) states [12]

Structural characteristics	*DR*			*WR*		
	mean	*SD*	*CV*, %	mean	*SD*	*CV*, %
WPC, loops/cm	13.81	0.02	0.16	14.76	0.22	1.48
CPC, loops/cm	10.56	0.10	0.91	10.72	0.11	0.76
S, loops/cm^2	145.87	1.11	0.76	158.24	3.63	2.30
l_1, mm	4.96	0.04	0.89	4.93	0.04	0.65
l_2, mm	4.86	0.03	0.59	4.85	0.04	0.86
l_a, mm	4.91	0.03	0.65	4.89	0.04	0.84
W, g/m^2	261.28	11.18	4.28	302.14	3.87	1.28
T, mm	1.25	0.01	1.07	1.33	0.05	3.43
WPC – the number of wales per centimeter, *CPC* – the number of courses per centimeter, *S* – stitch density, l_1 – stitch length for a 1x1 rib stitch, l_2 – stitch length for a plain stitch, l_a – average stitch length, *W* - weight, *T* – thickness, *SD* – standard deviation, *CV* – coefficient of variation						

The presented results (Table 2) show clear differences between the dry relaxed (*DR*) and wash relaxed (*WR*) states, indicating structural rearrangement of the knitted fabric after washing. The number of wales per centimeter (*WPC*) rises from 13.81 to 14.76 loops/cm, representing an increase of approximately 6.8%, while the number of courses per centimeter (*CPC*) increases slightly from 10.56 to 10.72 loops/cm (1.5%). Consequently,

stitch density (*S*) increases from 145.87 to 158.24 loops/cm², representing an 8.5% increase, indicating overall fabric compaction.
In contrast, the stitch length remains largely unchanged after washing. For the 1x1 rib stitch, the stitch length (l_1) slightly decreases from 4.96 mm to 4.93 mm, representing a 0.6% decrease. Meanwhile, the stitch length of the plain stitch (l_2) remains nearly unchanged (0.1%). As a result, the average stitch length (l_a) remains unchanged (0.4%), reflecting the stabilizing effect of the plain stitch on the overall trend.
Fabric weight (*W*), or mass per unit area, increases from 261.28 g/m² to 302.14 g/m² (15.7%), while thickness (*T*) rises from 1.25 mm to 1.33 mm (6.4%), indicating a denser, bulkier structure. This trend can be explained by the increasing number of wales per centimeter and the resulting increase in fabric stitch density, with a slight decrease in stitch length.
Overall, washing increases fabric stitch density, weight, and thickness, accompanied by slight reductions in stitch length, thereby confirming fabric shrinkage and structural consolidation after wet relaxation.
Statistical analysis using a *t*-test for dependent samples (Table 3) confirms the results obtained for the structural characteristics of the cotton Milano rib fabric.

Table 3: Statistical results of the structural characteristics of cotton Milano rib knitted fabric determined by using the *t*-test for dependent samples [12]

t value	Values of parameter *t* based on washing for the tested parameters ($df=n-1=4$ for *WPC*, *CPC*, *S*, *W*, *T*) ($df=n-1=9$ for l_a)					
	WPC	*CPC*	*S*	l_a	*W*	*T*
$t_{DR/WR}$	-8.73(***)	-4.00(*)	-8.88(***)	1.55(/)	-9.63(***)	-3.78(*)

WPC – the number of wales per centimeter, *CPC* – the number of course per centimeter, *S* – fabric stitch density, l_a – average stitch length, *W* – weight, *T* – thickness, *DR* – dry relaxed state, *WR* – wash relaxed state, (*) – 0.05 level of significance, (***) – 0.001 level of significance, (/) - no statistically significant difference, *df* – degrees of freedom, *n* – sample size

3.3. Bending properties of the knitted fabric

As previously mentioned, the bending behavior of the cotton Milano rib knitted fabric studied was assessed using the drape coefficient, number of nodes, bending stiffness, and bending modulus.
Top view of the real drape image and drape profile for the cotton Milano rib knitted fabric in dry relaxed and wash relaxed states are presented in Figure 2.
The results for the drape coefficient (K_d), the number of nodes (*N*), the bending stiffness (*B*), and bending modulus (*E*) values of the cotton Milano rib knitted fabric, measured in dry relaxed (*DR*) nd wash relaxed (*WR*) states, are shown in Table 4.

(a) (b) (c) (d)

Figure 2: Top view of the real drape image and drape profile for the cotton Milano rib knitted fabric in dry relaxed (a, b), and wash relaxed states (c, d)

Table 4: The results of the bending properties of the cotton Milano rib fabric

Fabric state	Parameter	Value of the tested parameter					
		K_d	N	B_{wales}	$B_{courses}$	E_{wales}	$E_{courses}$
DR	mean	40.66	3.83	$4.85 \cdot 10^{-7}$	$1.21 \cdot 10^{-7}$	99177.95	24808.61
	SD	1.85	0.41	$5.69 \cdot 10^{-8}$	$3.98 \cdot 10^{-8}$	11626.73	8136.35
	CV, %	4.55	10.65	11.72	32.80	11.72	32.80
WR	mean	45.04	4.00	$5.58 \cdot 10^{-7}$	$1.29 \cdot 10^{-7}$	94492.10	21884.12
	SD	2.06	0.00	$1.91 \cdot 10^{-7}$	$4.59 \cdot 10^{-8}$	32294.98	7771.92
	CV, %	4.57	0.00	34.18	35.51	34.18	35.51

K_d – drape coefficient, *N* – the number of nodes, *B* – bending stiffness, *E* – bending modulus, *DR* – dry relaxed state, *WR* – wash relaxed state, *SD* – standard deviation, *CV* – coefficient of variation

The results indicate that washing affects the bending properties of the cotton Milano rib fabric. The drape coefficient (K_d) rises from 40.66 in the dry relaxed state (*DR*) to 45.04 in the wash relaxed state (*WR*), an increase of 10.8%, showing that the fabric becomes stiffer and less drapable after washing. This change is also reflected in the drape image and profile (Figure 2), as well as in the number of nodes (*N*) measured in the dry relaxed (*DR*) and wash relaxed (*WR*) states (Table 4), suggesting certain structural alterations on the fabric surface following washing.

Bending stiffness (*B*) increases in both wale and course directions after washing, from $4.85 \cdot 10^{-7}$ to $5.58 \cdot 10^{-7}$ (by 15.1%) in wale direction and from $1.21 \cdot 10^{-7}$ to $1.29 \cdot 10^{-7}$ (by 6.6%) in course direction, although high variability is observed ($CV > 34\%$), reflecting non-uniform changes in fabric behavior. In contrast, the bending modulus (*E*) decreases slightly after washing – from 99,177.95 to 94,492.10 (by 4.8%) in wale direction and from 24808.61 to 21884.12 (by 11.8%) in course direction – indicating that while localized stiffness may increase, the fabric overall becomes somewhat more flexible in bending.

Statistical results of the bending properties of cotton Milano rib knitted fabric determined by using the *t*-test for dependent samples are presented in Table 5. Statistical analysis using a *t*-test showed that washing statistically significantly increased only the drape coefficient.

Table 5: Statistical results of the bending properties of cotton Milano rib knitted fabric determined by using the *t*-test for dependent samples

t value	Values of parameter *t* based on washing ($df=n-1=5$ for K_d and N) ($df=n-1=4$ for B and E)					
	K_d	N	B_{wales}	$B_{courses}$	E_{wales}	$E_{courses}$
$t_{DR/WR}$	-4.10(**)	-1.00(/)	-0.90(/)	-0.25(/)	0.34(/)	0.50(/)

K_d – drape coefficient, N – the number of nodes, B – bending stiffness, E – bending modulus, DR – dry relaxed state, WR – wash relaxed state, (**) – 0.01 level of significance, (/) - no statistically significant difference, df – degrees of freedom, n – sample size

Overall, washing results in a slightly stiffer fabric, with minor structural changes, highlighting the complex impact of washing on fabric performance.

4. CONLCUSIONS

Investigation of the effects of washing on the bending properties of cotton Milano rib fabric revealed that washing induces notable dimensional and mechanical changes. The fabric exhibits shrinkage in both wale and course directions (~5.4%). Structural rearrangements are evident, with increases in the stitch density, while stitch length remains largely unchanged, helping stabilize the fabric structure. Fabric weight and thickness increase by 15.7% and 6.4%, resulting in a denser, slightly bulkier fabric. Mechanically, the fabric becomes stiffer and less drapable: the drape coefficient rises by 10.8%, bending stiffness increases by 15.1% in the wale direction and by 6.6% in the course direction, while the bending modulus decreases. These results demonstrate that washing produces subtle yet significant modifications in both dimensional and bending properties, highlighting the complex impact of washing on fabric performance and stability.

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COMPREHENSIVE CHARACTERIZATION AND PERFORMANCE MAPPING OF KNITTED ARCHITECTURES FOR ACTIVE SPORTSWEAR APPLICATIONS

Review paper
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ABSTRACT: *Advanced engineering of athletic apparel requires an intricate understanding of mechanical, structural, and thermo-physiological behavior under conditions of intense activity and regular maintenance cycles. This study presents an exhaustive experimental mapping and characterization of 26 separate knitted fabric specimens manufactured from a cross-section of primary apparel materials, including natural cotton, virgin polyester (PES), recycled polyester (REC PES), and elastane (EA) blends across multiple stitch arrangements (single jersey, three-yarn fleece, mesh, rib, piqué, interlock, and spacer configurations). The experimental framework comprised the full 16-stage testing pipeline: atmospheric conditioning, fabric mass, stitch density profiling, pneumatic bursting pressure, ball burst strength, Martindale abrasion failure cycles, pilling evaluation, multi-axial extension and elastic recovery, strip-tensile breaking strength, washing dimensional shrinkage, loop spirality deformation, air permeability, vertical capillary moisture wicking, washing color fastness, dry/wet crocking fastness, perspiration fastness under acidic/alkaline media, and phenolic yellowing storage risks. The empirical findings demonstrated that while 100% cotton specimens provide exceptional initial soft touch and moisture intake, they fail core industrial durability metrics, yielding severe lengthwise washing contraction up to -13.3% and loop spirality up to 5.8%. In contrast, dense double-knit structures, notably 100% PES Interlock variants, exhibited supreme structural locking and an unprecedented ball burst resistance of 981.0 N. Recycled synthetic variants achieved technical and performance parity with virgin counterparts across all mechanical and fastness parameters. Based on this multidimensional data pool, a localized zoning structural matrix (body mapping layout) is proposed for engineered athletic jersey optimization.*

Keywords: *Active Sportswear, Knitted Configurations, Comprehensive Testing Pipeline, Mechanical Parity, Structural Integrity, Thermo-Physiological Ergonomics.*

SVEOBUHVATNA KARAKTERIZACIJA I MAPIRANJE PERFORMANSI PLETENIH STRUKTURA ZA PRIMENU U AKTIVNOJ SPORTSKOJ ODEĆI

APSTRAKT: *Napredno inženjerstvo sportske odeće zahteva detaljno razumevanje mehaničkog, strukturnog i termo-fiziološkog ponašanja u uslovima intenzivne aktivnosti i redovnih ciklusa održavanja. Ova studija predstavlja iscrpno eksperimentalno mapiranje i karakterizaciju 26 različitih uzoraka pletenih tkanina proizvedenih od preseka primarnih materijala za odeću, uključujući prirodni pamuk, devičanski poliester (PES), reciklirani poliester (REC PES) i mešavine elastana (EA) kroz višestruke aranžmane prepleta (singl džersi, trožilni flis, mrežasti, rebrasti, pike, interlok i spejser konfiguracije). Eksperimentalni okvir obuhvatio je kompletan lanac ispitivanja od 16 faza: atmosfersko kondicioniranje, masu tkanine, profilisanje gustine petlji, pneumatski pritisak rasprskavanja, otpornost na rasprskavanje čeličnom kuglom, cikluse oštećenja usled Martindale abrazije, procenu pilinga, višeosno izduženje i elastični oporavak, otpornost na kidanje trake, dimenziono skupljanje pri pranju, deformaciju spiralnosti petlji, propusnost vazduha, vertikalno kapilarno odvođenje vlage, postojanost boje pri pranju, postojanost na suvo/mokro trljanje, postojanost na znoj u kiseloj/alkalnoj sredini i rizike od fenolnog žućenja tokom skladištenja. Empirijski nalazi su pokazali da, iako uzorci od 100% pamuka pružaju izuzetan početni mek dodir i upijanje vlage, oni ne ispunjavaju ključne industrijske metriker trajnosti, pokazujući ozbiljno uzdužno skupljanje pri pranju do -13,3% i spiralnost petlji do 5,8%. Nasuprot tome, guste dvostruko pletene strukture, posebno varijante 100% PES Interloka, pokazale su vrhunsko strukturno zaključavanje i neprevaziđenu otpornost na rasprskavanje kuglom od 981,0 N. Reciklirane sintetičke varijante postigle su tehnički i performansni paritet sa devičanskim pandanima u svim mehaničkim parametrima i parametrima postojanosti. Na osnovu ovog višedimenzionalnog skupa podataka, predložena je lokalizovana strukturna matrica zoniranja (izgled mapiranja tela) za optimizaciju projektovanih sportskih dresova.*

Ključne reči: *Aktivna sportska odeća, Pletene konfiguracije, Sveobuhvatni lanac ispitivanja, Mehanički paritet, Strukturni integritet, Termo-fiziološka ergonomija.*

1. INTRODUCTION

High-performance sportswear operates under unique engineering paradigms that differentiate it significantly from conventional lifestyle fashion. During athletic activities, garments undergo repeated complex stresses, including extreme multi-directional expansions, severe abrasive skin friction, and rapid environment-body humidity fluctuations. Consequently, structural integrity, durability, and moisture handling must be engineered simultaneously. Knitted configurations are universally preferred in this field due to their flexible loop configurations, which allow multi-axial elongation while accommodating muscle expansion without permanent structural bagging. This investigation establishes a holistic empirical baseline across 26 distinct commercial variants, exploring the full mechanical, dimensional, and comfort limitations to formulate an optimized performance layout matrix.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Material Specimen Profile

The research pipeline was executed across a meticulous assortment of 26 industrial-grade knitted specimens. To achieve full tracking, all 26 materials, along with their precise knitting architecture, areal mass, raw fiber composition, and geometric loop distributions, are detailed in Table 1.

Table 1: The list of materials

Sample ID	Knitting Construction Type	Fabric Mass (g/m²)	Raw Material Blend Composition	Wales per cm (Wpc)	Courses per cm (Cpc)
M1	Single Jersey	140	100% Cotton	14.0	18.5
M2	Single Jersey	160	100% Cotton	13.5	17.0
M3	Single Jersey	180	100% Cotton	12.0	15.5
M4	Single Jersey	150	65% Polyester / 35% Cotton	14.5	19.0
M5	Single Jersey	170	88% Recycled PES / 12% Elastane	16.5	22.0
M6	Single Jersey	165	92% Polyester / 8% Elastane	16.0	21.5
M7	Mesh / Filet Openwork	140	100% Recycled PES	10.0	12.0
M8	Mesh / Filet Openwork	130	100% Polyester	10.5	11.5
M9	Mesh / Filet Openwork	150	100% Recycled PES	9.5	12.5
M10	Mesh / Filet Openwork	160	95% Polyester / 5% Elastane	11.0	13.0
M11	Rib 1x1 Configuration	220	100% Cotton	11.5	14.0
M12	Rib 1x1 Configuration	240	100% Cotton	11.0	13.5
M13	Rib 1x1 Configuration	255	100% Polyester	11.0	14.5

Sample ID	Knitting Construction Type	Fabric Mass (g/m²)	Raw Material Blend Composition	Wales per cm (Wpc)	Courses per cm (Cpc)
M14	Rib 1x1 Configuration	270	100% Cotton	10.0	13.0
M15	Rib 2x2 Configuration	280	95% Cotton / 5% Elastane	9.5	12.0
M16	Rib 2x2 Configuration	290	100% Polyester	9.0	13.0
M17	Three-Yarn Fleece	320	100% Cotton	9.5	12.0
M18	Three-Yarn Fleece	360	100% Cotton	9.0	11.5
M19	Three-Yarn Fleece	400	65% Cotton / 35% Polyester	8.5	11.5
M20	Three-Yarn Fleece	440	100% Cotton	8.5	11.0
M21	Piqué Construction	180	100% Cotton	12.5	16.0
M22	Piqué Construction	200	65% Polyester / 35% Cotton	12.0	15.5
M23	Piqué Construction	190	100% Recycled PES	13.0	16.5
M24	Interlock Double-Knit	140	100% Cotton	15.5	20.0
M25	Interlock Double-Knit	150	100% Polyester	15.0	19.0
M26	Spacer / 3D Sandwich	270	70% Cotton / 30% Recycled PES	12.0	15.5

Comprehensive 16-Stage Standardized Testing Pipeline

- 1. Specimen Atmospheric Conditioning (ISO 139): Samples exposed for 24 hours at 20 ± 2 °C and 65% ± 5% RH.
- 2. Fabric Mass per Unit Area (Areal Weight - ISO 3801): Measured using circular 100 cm² die cutters and digital balances.
- 3. Stitch Density Profiling: Wales per cm (Wpc) and Courses per cm (Cpc) mapped using standard illuminated textile loupes.
- 4. Pneumatic Diaphragm Bursting Strength (ISO 13938-1): Applied circular hydraulic diaphragm pressure across a 50 cm² window until loop burst failure.

- 5. Steel Ball Burst Strength (ASTM D6797): Polished steel 25.4 mm sphere pushed through fabrics using CRE columns to check peak force.
- 6. Martindale Abrasion Resistance and Lifetime Failure (ISO 12947-2): Specimen rubbed under 9 kPa payload against wool fabrics up to 50,000 cycles.
- 7. Martindale Pilling and Surface Fuzzing Degradation (ISO 12945-2): Face-to-face rubbing scored via standard comparative cards (Grade 1-5).
- 8. Multi-Axial Elastic Extension and Recovery (ASTM D2594): Tracked expansion capability and residual structural deformation after static relaxation.
- 9. Strip Tensile Strength and Breaking Elongation (ISO 13934-1): Pulled 50 mm wide stripes across a 200 mm span on axial columns.
- 10. Laundering Dimensional Stability / Shrinkage Tracking (ISO 5077 / ISO 6330): Calculated post-laundering loop contraction at 40°C.
- 11. Loop Spirality and Distortion Torque (ISO 6330 / AATCC 179): Checked structural torque skewness following automated laundering.
- 12. Pneumatic Air Permeability (ISO 9237): Calculated vertical air passage velocity at a fixed differential pressure of 100 Pa.
- 13. Thermo-Physiological Vertical Capillary Wicking (AATCC 197): Tracked distilled water capillary elevation along vertical fabric ribbons.
- 14. Color Fastness to Home Laundering (ISO 105-C06): Scored accelerated shade loss and multi-fiber transfer using Grey Scales.
- 15. Color Fastness to Crocking and Friction Rubbing (ISO 105-X12): Motorized dry/wet rubbing tracks evaluating mechanical stain transfer.
- 16. Color Fastness to Human Perspiration (ISO 105-E04): Incubated multi-fiber sand specimens in artificial body chemistry solutions at 37°C for 4 hours.
- 17. Storage Phenolic Yellowing Tendency (ISO 105-X18): Oven-packed wrap testing investigating nitrogen oxide storage oxidation hazards.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Extensive Structural and Mechanical Strength Diagnostics

The experimental mapping of mechanical resilience revealed clear performance boundaries based on knitting architecture and raw material composition. Single knit frameworks (M1 to M6) demonstrated a baseline ball burst strength profile ranging between 286.5 N and 474.8 N. Three-yarn fleeces (M17 to M20) demonstrated higher resistance (363.6 N to 524.0 N) due to the presence of heavy inlay backing yarns woven behind the face loops. The absolute performance peak was achieved by M25 (100% Polyester Interlock), which recorded an extraordinary ball burst threshold of 981.0 N and pneumatic bursting pressure exceeding 780 kPa. The structural locking mechanism of the interlock matrix distributes multi-axial stress evenly across both yarn planes, preventing early stitch collapse. The complete experimental data pool is provided in Table 2.

Table 2: The complete experimental data pool

ID	Ball Burst (N)	Pneumatic Burst (kPa)	Abrasion (Cycles)	Pilling Grade	Shrinkage (%)	Spirality (%)	Air Perm. (mm/s)	Wicking (mm)
M1	310.2	295	22,000	3	-11.5	4.8	185	85
M2	422.2	310	25,000	3	-13.3	5.2	170	90
M3	455.0	340	28,000	3-4	-12.0	5.8	155	95
M4	510.5	420	38,000	4	-5.2	2.1	210	75
M5	645.8	580	>50,000	4-5	-1.1	0.0	285	120
M6	612.0	550	>50,000	4-5	-1.4	0.0	260	115
M7	529.0	480	>50,000	4-5	-0.8	0.0	445	145
M8	512.4	465	>50,000	4-5	-0.9	0.0	460	140
M9	540.6	490	>50,000	4-5	-0.7	0.0	430	148
M10	585.2	520	>50,000	4	-1.8	0.0	395	130
M11	385.4	320	24,000	3	-10.8	0.0	240	100
M12	410.2	350	26,000	3	-11.3	0.0	220	105
M13	680.5	610	>50,000	4-5	-1.2	0.0	310	125
M14	440.0	365	27,000	3	-11.1	0.0	205	110
M15	495.6	410	32,000	3-4	-4.5	0.0	250	115
M16	710.2	640	>50,000	4-5	-1.0	0.0	295	130
M17	363.6	390	18,000	2	-9.5	1.2	120	70
M18	415.0	425	20,000	2	-10.2	0.8	110	75
M19	490.8	495	34,000	3	-4.1	0.5	135	65
M20	524.0	530	22,000	2-3	-10.5	0.9	95	80
M21	390.4	340	25,000	3-4	-8.4	1.5	190	90
M22	540.2	460	40,000	4	-3.2	0.6	225	80
M23	595.6	510	>50,000	4-5	-0.9	0.0	245	120
M24	435.0	380	28,000	4	-9.0	0.0	140	95
M25	981.0	785	>50,000	5	-2.1	0.0	165	135
M26	745.2	690	42,000	4	-6.4	0.0	280	110

3.2. Dimensional Stability, Torque Skewness, and Comfort Characterization

Laundering exposures emphasized the primary risk factors and dimensional instabilities of natural fibers. Specimen M2 (100% Cotton Single Jersey) exhibited severe structural contraction, reaching a critical -13.3% shrinkage along the courses (lengthwise) direction. This *büzülme* (dimensional contraction) stems directly from relaxation shrinkage, where mechanical viscoelastic strains frozen inside the loops during manufacturing unlock upon exposure to water. The moisture acts as a plasticizer, releasing the stored tension and forcing the distorted loops to revert to their thermodynamic equilibrium state.

Furthermore, M2 failed the industrial skewness criteria, displaying a spirality torque of 5.2%, while M3 reached an even higher 5.8%. Both samples exceeded the standard industrial performance ceiling of ≤5.0%. This twisting defect is driven by the residual torsional torque of the ringspun yarns, which causes loop tilt once the fabric is wetted.
Conversely, Specimen M25 (Interlock) displayed robust geometric invariance, with negligible shrinkage values of -1.5% crosswise and -2.1% lengthwise. This superior stability is due to the structural symmetry of the interlock architecture; its back-to-back double-knit construction effectively counteracts internal mechanical stresses and neutralizes yarn torque, preventing both shrinkage and spirality.

3.3. Multi-Axial Elasticity and Environmental Fastness Records

Elastic extension profiles proved that knitting geometry dictates raw stretchability, but yarn composition controls elastic recovery. Material M14 (Cotton Rib) recorded a high crosswise extension of 122.5% under standard load, yet its recovery was highly inefficient, leaving a severe permanent deformation with only a 73.7% recovery rate. This poor recovery is due to the plastic deformation behavior of natural cotton fibers, which lack the molecular elasticity to overcome the structural displacement of the rib loops.
Conversely, Material M13 (Synthetic PES Rib) limited its elongation to 54.4% but showed an exceptional 99.0% elastic recovery rate, locking back perfectly to its original shape thanks to the high resilience and synthetic polymer memory of polyester. Additionally, fastness metrics across wash, rubbing, and sweat tracks showed stable Grade 4-5 performance for the synthetics, confirming that the synthetic fibers offer superior molecular stability against both mechanical and chemical degradation.

4. TECHNICAL IMPLEMENTATION MODEL (BODY MAPPING LAYOUT)

Synthesizing all 16 evaluation results, an optimal regional textile mapping for high-performance athletic wear is structured in Table 3.

Table 3: Optimal regional textile mapping for high-performance athletic wear

Anatomical Target Area	Selected Code	Fabric Architecture	Mass (gsm)	Raw Material Fiber Mix	Primary Engineering Rationale
Main Torso Core	M25	Interlock Knit	150	100% Polyester	981 N burst defense, high dimensional locking, optimal heat dissipation.
Collar & Cuffs	M13	Rib 1x1 Construction	255	100% Polyester	99% elastic shape recovery, contours smoothly without permanent sagging.
High-Sweat Aeration	M7	Open Mesh Filet	140	100% Recycled PES	High airflow, fast capillary sweat removal, ecodesign integration.

5. CONCLUSIONS

1. Pure natural cotton fibers fail active sportswear limits due to excessive washing contraction (-13.3%) and poor recovery kinetics (73.7%), regardless of their comfortable hand properties.
2. Double-knit synthetic geometries, specifically interlock structures, present superior structural security with a ball burst protection of 981.0 N and minimal shrinkage variations.
3. Recycled polyester configurations achieve mechanical and fastness parity compared to virgin synthetic paths, proving eco-friendly sportswear viability.
4. The implementation of body mapping, grouping interlock, high-elasticity ribs, and hyper-porous recycled mesh across specific biological layout regions, satisfies modern performance standards.

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QUANTITATIVE EVALUATION OF DOT PATTERN TRANSFER QUALITY ON THE FACE AND BACK SIDES OF PRINTED TEXTILE FABRICS

Scientific paper
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ABSTRACT: *The quality of printed textile structures is commonly evaluated visually, although objective image analysis provides more reliable and reproducible results. This study presents a quantitative assessment of circular dot patterns printed on textile fabric by comparing the face and back sides using digital image processing. Twelve printed dots were analyzed on each side, and several geometrical and quality parameters were calculated, including dot area, circularity, aspect ratio, roundness, solidity, pattern transfer ratio (PTR), dot fidelity index (DFI), contrast loss index (CLI), and pattern fidelity performance index (PFPI). The results indicate complete pattern detection on both fabric surfaces; however, significant degradation occurred after ink penetration through the fabric. The mean dot area decreased by 21.6%, circularity by 51.2%, and DFI by 51.2%, while CLI increased to 0.307, indicating moderate contrast degradation. According to the proposed grading system, the face side achieved Grade A, whereas the back side received Grade C. The proposed methodology provides an objective approach for evaluating print transfer quality and can support optimization of textile printing processes.*

Keywords: *textile printing, image analysis, digital image processing, pattern transfer, dot fidelity, print quality*

KVANTITATIVNA PROCENA KVALITETA PRENOSA TAČKASTOG UZORKA NA LICU I NALIČJU ŠTAMPANIH TEKSTILNIH MATERIJALA

APSTRAKT: *Kvalitet štampanih tekstilnih struktura najčešće se ocenjuje vizuelno, iako objektivna analiza slike pruža pouzdanije i reproduktivnije rezultate. U ovom radu predstavljena je kvantitativna procena kružnih tačkastih uzoraka odštampanih na tekstilnom materijalu poređenjem lica i naličja primenom digitalne obrade slike. Na svakoj strani analizirano je dvanaest odštampanih tačaka, pri čemu su izračunati različiti geometrijski i kvalitativni parametri, uključujući površinu tačke, kružnost, odnos osa, zaobljenost, punoću (solidity), odnos prenosa uzorka (Pattern Transfer Ratio – PTR), Indeks geometrijske očuvanosti oblika tačke (Dot Fidelity Index – DFI), indeks gubitka*

kontrasta (Contrast Loss Index – CLI) i indeks performansi vernosti uzorka (Pattern Fidelity Performance Index – PFPI). Rezultati ukazuju na potpunu detekciju uzorka na obe površine tkanine; međutim, nakon penetracije boje kroz tekstilni materijal uočena je značajna degradacija kvaliteta. Prosečna površina tačke smanjena je za 21,6%, kružnost za 51,2%, a geometrijska očuvanosti oblika tačke (DFI) za 51,2%, dok je indeks gubitka kontrasta (CLI) povećan na 0,307, što ukazuje na umerenu degradaciju kontrasta. Prema predloženom sistemu ocenjivanja, lice materijala svrstano je u kvalitetnu klasu A, dok je naličje ocenjeno klasom C. Predložena metodologija omogućava objektivan pristup oceni kvaliteta prenosa štampe i može doprineti optimizaciji procesa štampanja tekstilnih materijala.

Ključne reči: *Štampanje tekstila, analiza slike, digitalna obrada slike, prenos uzorka, indeks očuvanosti oblika tačke (DFI), kvalitet štampe.*

1. INTRODUCTION

The quality of textile printing is determined not only by accurate color reproduction but also by the geometric fidelity of printed motifs. During the printing process, pigments or dyes penetrate the textile structure, where fiber morphology, yarn configuration, and fabric porosity influence ink spreading, edge sharpness, and dimensional stability of the printed pattern [1,2]. Similar structural characteristics have also been shown to influence laundering behavior, dimensional stability, and the performance of functional textile materials, including antimicrobial chitosan-treated cotton yarns [3-8]. The effects of ink penetration are particularly evident on the reverse side of the fabric, where deformation of printed elements and reduction of image contrast may occur.

Traditionally, print quality has been evaluated by visual inspection or subjective comparison with reference samples. Although these methods are simple to perform, they are strongly dependent on the observer and environmental conditions, resulting in limited repeatability and reproducibility [9]. Consequently, objective evaluation techniques based on digital image processing have attracted considerable attention in textile quality control. Recent advances in digital image analysis have enabled accurate characterization of printed structures through quantitative morphological descriptors extracted from high-resolution images. Image-processing techniques have been successfully applied for evaluating textile print quality, print mottle, and the influence of printing parameters on print performance [10–12]. Furthermore, digital image analysis has proven to be an effective tool for objective characterization of other textile properties, including fabric drape behavior [13-15], as well as for quantitative evaluation and optimization of yarn-related parameters using hybrid image-based and statistical approaches [16]. Parameters such as area, circularity, aspect ratio, roundness, and solidity provide objective measures of geometric accuracy, dimensional stability, and deformation of printed patterns, thereby supporting quantitative assessment and optimization of textile printing processes.

Despite these advances, relatively little attention has been devoted to quantitative comparison of identical printed motifs on the face and back sides of textile materials. Objective evaluation of the morphological changes occurring during ink penetration can provide valuable information regarding print transfer behavior, geometric fidelity, and the influence of textile structure on print quality.
Therefore, the objective of this study was to quantitatively compare the geometry and transfer quality of circular printed dot patterns on the face and back sides of a textile fabric using digital image analysis. In addition to conventional morphological descriptors, the pattern transfer ratio (PTR), dot fidelity index (DFI), contrast loss index (CLI), and pattern fidelity performance Index (PFPI) were employed to objectively evaluate the preservation of print quality following ink penetration through the textile structure.

2. EXPERIMENTAL PART

2.1. Materials

The experimental investigation was carried out using a commercially available women's dress fabric purchased from the local retail market. The material was selected because it represents a typical lightweight apparel fabric commonly used in the garment industry. A regular polka-dot print consisting of dark-blue circular dots uniformly distributed on a white background was used as the test pattern for image analysis.
Based on visual inspection, the fabric exhibited a plain, smooth surface with a low-relief texture suitable for digital image acquisition. The circular printed dots were characterized by high color contrast with respect to the white background, facilitating accurate segmentation and quantitative evaluation. The regular spacing and nearly uniform diameter of the printed dots enabled direct comparison of their geometrical characteristics on the face and back sides of the fabric after print penetration.
The face side of the fabric, corresponding to the directly printed surface, and the back side, representing the reverse surface after ink penetration through the textile structure, were analysed separately. Digital photographs of both sides were acquired under identical illumination and imaging conditions using the same camera settings. A transparent metric ruler was included in each image to provide dimensional calibration for the conversion of pixel measurements into metric units (cm^2) during image processing.

2.2. Procedure

The printed textile sample was placed on a flat, uniform background and photographed under controlled lighting conditions. Images of the face and back sides were captured separately using the same camera position, distance, resolution, and illumination setup. Special attention was paid to avoiding shadows, reflections, and fabric distortion during image acquisition.
After image acquisition, the images were imported into image-analysis software. The circular printed dots were segmented from the background using threshold-based digital image processing. Each detected dot was labelled as an individual object, and objects not corresponding to printed dots were removed from the analysis.

For both fabric sides, the same segmentation procedure was applied in order to ensure comparable results. The number of detected dots, their surface area, and shape descriptors were calculated automatically from the segmented images.

2.3. Testing methods

The total number of detected dots was recorded as the number of successfully segmented circular printed dots within the selected region of interest. The mean dot area (cm^2) was calculated as the average projected area of the detected printed dots after calibration of the images from pixels to square centimetres. The coefficient of variation of the dot area (CV, %) was determined to evaluate the uniformity of the printed dots within the analysed region.

The geometrical characteristics of the printed dots were further evaluated using shape descriptors. Mean circularity was calculated as a dimensionless parameter describing the degree of similarity between the detected dot and a perfect circle, where a value of 1.0 corresponds to an ideal circular shape. Mean aspect ratio was calculated as the average ratio between the major and minor axes of the fitted ellipse for each printed dot and was used to evaluate possible directional deformation. Mean roundness was determined as an indicator of the smoothness and compactness of the printed dot contour, whereas mean solidity was calculated as the average ratio between the projected dot area and the corresponding convex hull area to quantify edge regularity and boundary integrity.

The efficiency of pattern transfer through the textile structure was evaluated using the pattern transfer ratio (PTR), calculated as the ratio between the mean dot area measured on the back side of the fabric and the corresponding mean dot area measured on the face side. The preservation of the original dot geometry after penetration through the textile material was assessed by the dot fidelity index (DFI), calculated as the ratio between the mean circularity values obtained from the back and face sides of the fabric.

The contrast loss index (CLI) was calculated as a normalized indicator describing the reduction in image contrast between the face and back sides caused by ink penetration through the textile structure. Furthermore, the pattern fidelity performance index (PFPI) was determined as a composite quality indicator integrating the effects of dot area preservation, geometric fidelity, and contrast retention, thereby providing an overall assessment of print quality after transfer through the textile material.

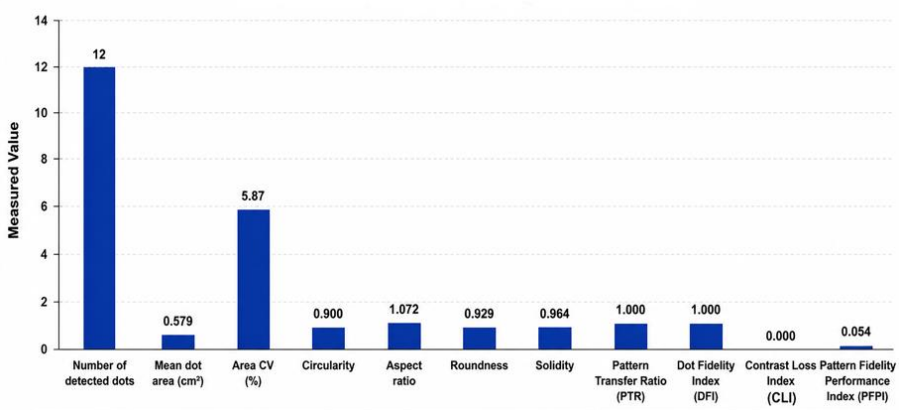
Finally, the calculated geometrical parameters and performance indices were used to assign an overall quality grade to the printed pattern. The grading system was established according to the level of preservation of the original printed geometry, where Grade A indicated excellent pattern preservation and progressively lower grades corresponded to increasing degradation of the printed pattern after transfer through the fabric.

3. RESULTS AND DISCUSSION

3.1. Evaluation of the face side

The quantitative image analysis of the face side demonstrated excellent print quality and served as the reference for evaluating pattern transfer through the textile structure (Figure 1). All twelve printed dots were successfully detected, indicating complete pattern

recognition without missing or merged objects. The mean projected dot area was 0.579 cm², reflecting the original dimensions of the printed motifs.
The geometrical descriptors confirmed a high degree of shape preservation. The mean circularity reached 0.900, indicating that the printed dots closely approximated an ideal circular geometry. Similarly, the mean roundness (0.929) and mean solidity (0.964) demonstrated smooth boundaries and compact dot morphology with minimal edge irregularities. The aspect ratio of 1.072 showed that the dots remained nearly circular with only negligible elongation.
As expected for the reference surface, the pattern transfer ratio (PTR) and dot fidelity index (DFI) were both equal to 1.000, indicating complete preservation of the original printed geometry. Furthermore, the contrast loss index (CLI) was equal to zero, confirming the absence of contrast degradation on the directly printed surface. Consequently, the face side achieved the highest pattern fidelity performance index (PFPI = 0.054) and was classified as Grade A, representing excellent print quality.



Detection	Morphological Descriptors						Quality Indices			
Number of detected dots	Mean dot area (cm²)	Area CV (%)	Circularity	Aspect ratio	Roundness	Solidity	PTR	DFI	CLI	PFPI
12	0.579	5.87	0.900	1.072	0.929	0.964	1.000	1.000	0.000	0.054

Notes: Area in cm²; CV = Coefficient of Variation; PTR = Pattern Transfer Ratio; DFI = Dot Fidelity Index; CLI = Contrast Loss Index; PFPI = Pattern Fidelity Performance Index.

Figure 1: Morphological and print quality parameters of face side of the printed fabric

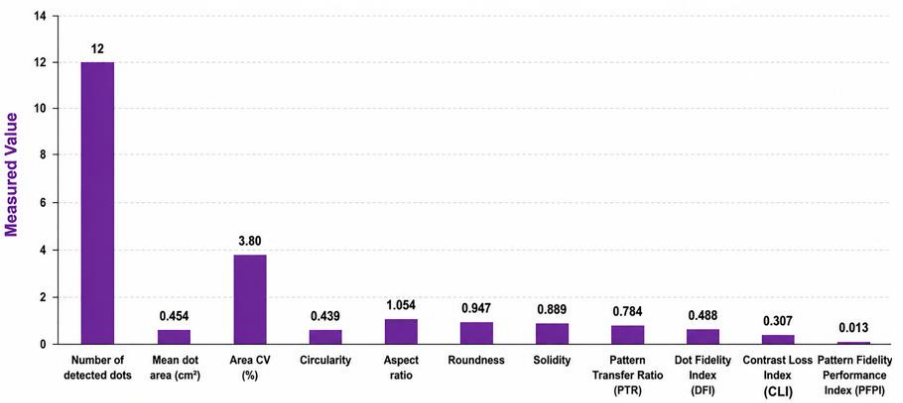
3.2. Evaluation of the back side

The image analysis of the back side revealed that all twelve printed dots remained detectable after penetration of the printing paste through the textile structure, confirming that complete pattern transfer had occurred (Figure 2). However, noticeable changes in both geometrical characteristics and print quality were observed.
The mean projected dot area decreased to 0.454 cm², indicating a reduction in the amount of transferred printed material. The coefficient of variation decreased from 5.87% to

3.80%, suggesting slightly improved size uniformity among the transferred dots despite the reduction in their average size.

More pronounced changes were observed in the shape descriptors. The mean circularity decreased to 0.439, indicating substantial deformation of the originally circular printed dots. Although the aspect ratio remained nearly unchanged (1.054), suggesting negligible directional elongation, the mean solidity decreased to 0.889, revealing increased edge irregularity after ink penetration through the textile structure. In contrast, the mean roundness slightly increased to 0.947, indicating that although the dots became smaller and less circular, their overall compactness remained relatively stable.

The calculated pattern transfer ratio (PTR = 0.784) indicated moderate transfer efficiency, whereas the dot fidelity index (DFI = 0.488) demonstrated that only approximately one-half of the original dot geometry was preserved after transfer. The contrast loss index increased to 0.307, confirming moderate deterioration of image contrast on the reverse side. Consequently, the pattern fidelity performance index decreased to 0.013, and the back side was classified as Grade C, indicating noticeable degradation of print quality.



Detection	Morphological Descriptors						Quality Indices			
Number of detected dots	Mean dot area (cm²)	Area CV (%)	Circularity	Aspect ratio	Roundness	Solidity	PTR	DFI	CLI	PFPI
12	0.454	3.80	0.439	1.054	0.947	0.889	0.784	0.488	0.307	0.013

Notes: Area in cm²; CV = Coefficient of Variation; PTR = Pattern Transfer Ratio; DFI = Dot Fidelity Index; CLI = Contrast Loss Index; PFPI = Pattern Fidelity Performance Index.

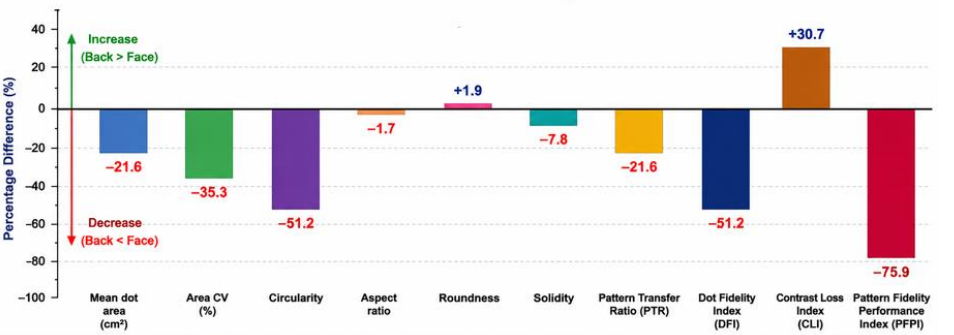
Figure 2: Morphological and print quality parameters of face side of the printed fabric

3.3. Comparative analysis between the face and back side

A comparative evaluation of the face and back sides of the printed textile fabric is presented in Figure 3. The comparative analysis demonstrated that penetration of the printing paste through the textile structure significantly influenced both the geometrical characteristics of the printed dots and the overall print quality. Although all twelve printed dots were successfully detected on both fabric surfaces, confirming complete pattern transfer,

substantial changes were observed in the morphological descriptors and quality indices after penetration.

The mean projected dot area decreased by 21.6%, indicating a reduction in the effective amount of transferred printing paste on the reverse side of the fabric. Simultaneously, the coefficient of variation of the dot area decreased by 35.3%, suggesting a slightly more uniform distribution of the transferred dot sizes despite the reduction in their average dimensions.



Parameter	Face side (Value)	Back side (Value)	Difference (Back – Face)	Difference (%)	Interpretation
Mean dot area (cm²)	0.579	0.454	−0.125	−21.6%	Area reduction after penetration ↓
Area CV (%)	5.87	3.80	−2.07	−35.3%	Improved size uniformity on back ↑
Circularity	0.900	0.439	−0.461	−51.2%	Strong boundary deformation ↓
Aspect ratio	1.072	1.054	−0.018	−1.7%	Shape elongation negligible ↔
Roundness	0.929	0.947	+0.018	+1.9%	Similar compactness ↔
Solidity	0.964	0.889	−0.075	−7.8%	Increased edge irregularity ↓
Pattern Transfer Ratio (PTR)	1.000	0.784	−0.216	−21.6%	Moderate transfer efficiency ↓
Dot Fidelity Index (DFI)	1.000	0.488	−0.512	−51.2%	Significant fidelity loss ↓
Contrast Loss Index (CLI)	0.000	0.307	+0.307	+30.7%	Moderate contrast degradation ↓
Pattern Fidelity Performance Index (PFPI)	0.054	0.013	−0.041	−75.9%	Strong quality decrease ↓

Summary

Parameters Increased (Back > Face)
- Roundness (+1.9%)
- Contrast Loss Index (+30.7%)

Parameters Decreased (Back < Face)
- Mean dot area (−21.6%)
- Area CV (−35.3%)
- Circularity (−51.2%)
- Aspect ratio (−1.7%)
- Solidity (−7.8%)
- PTR (−21.6%)
- DFI (−51.2%)
- PFPI (−75.9%)

Positive % → Increase (Back side greater than Face side) | Negative % → Decrease (Back side lower than Face side)

Figure 3: Comparison of the face and back sides of the printed textile fabric illustrating the influence of ink penetration on the geometrical characteristics and visual quality of the circular printed dots

The most pronounced geometrical degradation was observed for circularity, which decreased by 51.2%, indicating a considerable loss of the original circular geometry caused by interaction between the printing paste and the porous textile structure. A comparable reduction was obtained for the dot fidelity index (51.2%), confirming that the geometric fidelity of the printed motifs was significantly affected during penetration through the fabric. In contrast, the aspect ratio decreased by only 1.7%, demonstrating that the deformation occurred nearly isotropically without pronounced directional elongation.

Only minor changes were observed in roundness, which increased by 1.9%, indicating that the compactness of the transferred dots remained relatively stable. Conversely, solidity decreased by 7.8%, reflecting increased boundary irregularity and local edge deformation following ink penetration.

The pattern transfer ratio decreased from 1.000 to 0.784, indicating moderate transfer efficiency and confirming that approximately 78% of the original projected dot area was retained on the back side. Furthermore, the contrast loss index increased from 0.000 to 0.307, demonstrating moderate deterioration in image contrast and visual sharpness due to partial absorption and diffusion of the printing paste within the textile structure.
The cumulative effect of these morphological and optical changes was reflected by the pattern fidelity performance index, which decreased by 75.9%, representing the greatest relative reduction among all evaluated parameters. Consequently, the overall print quality classification decreased from Grade A for the face side to Grade C for the back side, indicating substantial deterioration of pattern fidelity after transfer through the textile material.

4. CONCLUSION

A digital image analysis methodology was developed for the objective evaluation of print quality on the face and back sides of printed textile fabrics. The proposed approach combined morphological descriptors with the pattern transfer ratio (PTR), dot fidelity index (DFI), contrast loss index (CLI), and pattern fidelity performance index (PFPI) to quantitatively characterize print quality and the effects of ink penetration through the textile structure. The face side exhibited excellent print quality, characterized by high circularity, regular dot morphology, and the highest overall quality grade (Grade A), confirming accurate reproduction of the printed pattern. In contrast, ink penetration through the textile structure resulted in reduced dot area, lower geometric fidelity, and increased contrast loss on the back side, leading to a decrease in print quality to Grade C. The proposed methodology provides a rapid, objective, and reproducible tool for evaluating print quality and the influence of ink penetration on printed textile fabrics. The approach can support quality control and optimization of textile printing processes by enabling quantitative assessment of both print fidelity on the face side and penetration effects on the reverse side.

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9. Međunarodna naučna konferencija
*„**Savremeni trendovi i inovacije u tekstilnoj industriji**“*
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INVESTIGATION OF THE STRUCTURAL AND PERFORMANCE PROPERTIES OF ELASTANE-CONTAINING FABRICS

Scientific paper
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ABSTRACT: *Elastane-containing fabrics are widely used in textile applications due to the comfort and flexibility they provide. Despite these advantages, various problems such as pilling, dimensional changes, surface deterioration, and elastane protrusion may occur during use and care processes, affecting both the appearance and performance of the fabric. Therefore, evaluating the structural and performance properties of elastane-containing fabrics is important for assessing their serviceability and quality. Accordingly, this study aimed to investigate the structural and performance characteristics of a plain-woven fabric composed of 90% polyester and 10% elastane. For this purpose, a series of physical, mechanical, surface, and color-related tests were conducted, including fabric weight, thickness, warp and weft density, fabric and yarn tensile strength, air permeability, pilling resistance, color measurement, laundering fastness, and rubbing fastness. In addition, test results provided by the manufacturer were incorporated into the evaluation and compared with the laboratory findings.The results indicated that the investigated fabric exhibited generally favorable performance in terms of structural properties, strength behavior, surface appearance, and color durability. No significant surface deterioration or elastane protrusion was observed during the surface evaluations, while the fastness tests demonstrated satisfactory resistance to laundering and rubbing conditions. Overall, the findings suggest that the 90% polyester / 10% elastane plain-woven fabric possesses suitable performance characteristics for its intended end-use applications.*

Keywords: *Elastane, Elastane Fabric, Woven Fabric, Fabric Performance, Elastane-containing fabric.*

ISPITIVANJE STRUKTURNIH I PERFORMANSNIH SVOJSTAVA TKANINA KOJE SADRŽE ELASTAN

APSTRAKT: *Tkanine koje sadrže elastan široko se koriste u tekstilnim primenama zbog udobnosti i fleksibilnosti koje pružaju. Uprkos ovim prednostima, tokom upotrebe i procesa održavanja mogu se javiti različiti problemi, kao što su piling, dimenzionalne promene, površinska degradacija i izbijanje elastanskih vlakana, koji utiču kako na izgled tako i na performanse tkanine. Stoga je ispitivanje strukturnih i performansnih svojstava tkanina sa elastanom od velikog značaja za procenu njihovog kvaliteta i upotrebne vrednosti. U skladu sa tim, cilj ovog rada bio je ispitivanje strukturnih i performansnih karakteristika platnene tkanine sastavljene od 90% poliestera i 10% elastana. U tu svrhu sprovedena su fizička, mehanička, površinska i kolorimetrijska ispitivanja, uključujući određivanje površinske mase, debljine, gustine osnove i potke, zateznih svojstava tkanine i pređe, propustljivosti vazduha, otpornosti na piling, merenje boje, postojanosti boje pri pranju i postojanosti boje na trljanje. Pored toga, rezultati ispitivanja dostavljeni od strane proizvođača uključeni su u analizu i upoređeni sa laboratorijskim nalazima. Ispitivana tkanina pokazala je generalno povoljne performanse u pogledu strukturnih svojstava, mehaničkog ponašanja, izgleda površine i postojanosti boje. Tokom površinskih ispitivanja nisu uočeni značajna površinska degradacija niti izraženo izbijanje elastanskih vlakana, dok su ispitivanja postojanosti boje pokazala zadovoljavajuću otpornost na pranje i trljanje. Sveukupno, dobijeni rezultati ukazuju da platnena tkanina sa sastavom 90% poliester / 10% elastan poseduje odgovarajuće performansne karakteristike za svoju predviđenu namenu.*

Ključne reči: *Tkanina sa elastanom, mešavina poliester/elastan, platneno tkanje, mehanička svojstva, površinske performanse, postojanost boje*

1. INTRODUCTION

In recent years, fabrics containing elastane have become widely used in the textile industry due to their high stretchability, freedom of movement, and wearing comfort (Shobanasree, Prakash, Kumar, Lokesh, & Manickam, 2022; Gorjanc & Bukošek). Even when elastane fibers are included in the fabric structure at low rates of only 2–3%, they can provide the desired level of elasticity, body conformity, and the ability to return to their original shape after deformation (Geleri, Gürarda, & Çeven, 2021; Senthilkumar, 2011). Therefore, elastane has become an important fiber, especially preferred in casual wear, sportswear and form-fitting garments (Senthilkumar, 2011). The addition of elastane has significant effects on the physical and performance properties of fabrics. Literature reports that fabrics containing elastane have increased gram weight (GSM) and thickness values, and also cause changes in air permeability, pilling behavior, stitch density, bursting strength and tensile properties (Azim, Sowrov, Ahmed, Ul Hasan, & Faruque, 2014; Jovanović, Penava, & Vrljicak, 2022). However, various quality problems such as loss of elasticity, permanent deformation, dimensional changes, pilling, fuzz formation, color change and elastane protrusion from the fabric surface can occur in elastane fabrics during use and maintenance (Bolaji & Dolez, 2024). Among these problems, elastane protrusion is considered a

significant defect that negatively affects the aesthetic appearance and can reduce the mechanical performance and lifespan of the fabric. Therefore, identifying the factors that cause elastane protrusion and examining the effects of this defect on fabric performance is important for improving the quality and durability of elastane-containing textile products.

2. MATERIALS AND METHOD

A plain-woven fabric containing 90% polyester (PES) and 10% elastane was used as the experimental material. The fabric was supplied by DressBest. The fabric is commonly used in uniform manufacturing, and the aim of this study was to evaluate its structural and performance properties. The experimental tests were carried out at the Istanbul Textile Research R&D and Innovation Center of Marmara University. In addition, the test results obtained from DressBest's in-house laboratory evaluations were incorporated into the analysis. As a result of the measurements, the fabric weight was determined as an average of 193 g/m², while the fabric thickness was measured as 0.56 mm The warp and weft density were determined to be 27 threads/cm.

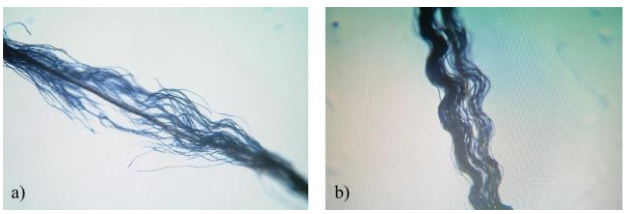

Figure 1: a) Microscopic appearance of the warp yarn b) Microscopic appearance of the weft yarn

2.1 Fabric Tensile Properties

The tensile properties of the fabric samples were determined according to ISO 13934-1. Tests were performed separately in the warp and weft directions, and the obtained breaking strength and breaking elongation values are given in graphical form.

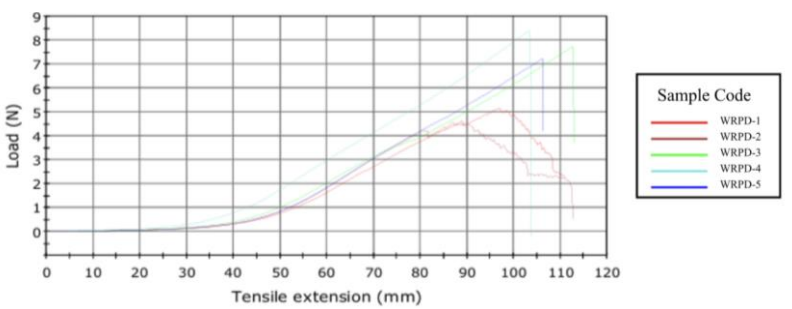

Figure 2: Load–Elongation Behavior of Fabric Samples in the Warp Direction

The graph shows a comparative analysis of the load-elongation behavior of the samples. The samples showed increasing elongation with increasing applied load, and breaking occurred after reaching the maximum load.

Table 1: Tensile Properties of Fabric Samples in the Warp Direction

Sample Code	Maximum Force (N)	Elongation at Break (mm)	Elongation at Maximum Force (%)
WRPD-1	5,17	110,78	48,47
WRPD2	4,63	112,46	44,48
WRPD-3	7,70	112,63	56,31
WRPD-4	8,36	103,62	51,56
WRPD-5	7,23	106,13	53,07
Mean	6,62	109,12	50,78
Maximum	8,36	112,63	56,31
Standard Deviation	1,63	4,04	4,51
CV (%)	24,65	3,71	8,89

The average maximum load value in the warp direction was determined to be 6.62 N, and the average elongation at break was 109.12 mm. The similarity of the elongation at break values indicates that the fabric exhibits similar stretching behavior in the warp direction. The average elongation value of 50.78% at maximum load shows that the fabric exhibits a significant elongation behavior under tensile force depending on its elastane content.

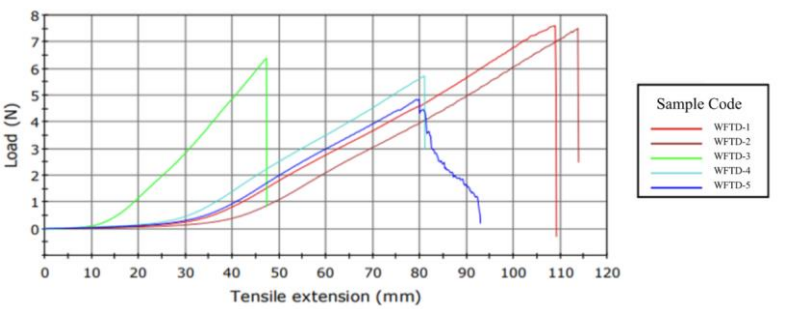

Figure 3: Load–Elongation Behavior of Fabric Samples in the Weft Direction

Table 2: Tensile Properties of Fabric Samples in the Weft Direction

Sample Code	Maximum Force (N)	Elongation at Break (mm)	Elongation at Maximum Force (%)
WRPD-1	7,60	108,96	54,31

WRPD2	7,50	113,61	56,81
WRPD-3	6,38	47,30	23,65
WRPD-4	5,72	80,97	40,40
WRPD-5	4,85	92,80	39,65
Mean	6,41	88,73	42,96
Maximum	7,60	113,61	56,81
Standard Deviation	1,17	26,56	13,33
CV (%)	18.30	29,93	31,03

According to the tensile test results in the weft direction, the average maximum load value was determined as 6.41 N. The average elongation at breaking was obtained as 88.73 mm. The average elongation value at maximum load was determined as 42.96%. Although there is no significant difference in maximum load values between the samples, more significant differences are observed in the elongation at breaking values. In particular, the fact that sample WRPD-3 shows a lower elongation at breaking of 47.30 mm compared to the other samples indicates that the elongation behavior in the weft direction is more variable. When compared with the warp direction results, it is seen that the average maximum load value in the weft direction is at a similar level, but the elongation at breaking value is lower. This situation reveals that the fabric exhibits a more limited and variable elongation behavior under tensile force in the weft direction compared to the warp direction.

2.2 Yarn Tensile Properties

The tensile properties of the warp and warp yarns were evaluated according to ISO 2062.

Table 3: Tensile Properties of Warp Yarns

Sample Code	Maximum Force (N)	Elongation at Break (mm)	Elongation at Maximum Force (%)
1	0,32	65,53	26,11
2	0,30	63,42	25,27
3	0,32	65,51	25,93
4	0,31	66,78	26,61
5	0,32	68,45	27,13
6	0,31	59,78	23,81
7	0,29	58,45	23,28
8	0,32	73,53	29,31
9	0,30	65,61	26,14
10	0,31	72,29	28,64
11	0,31	64,80	25,42
12	0,30	66,10	26,12

13	0,32	65,40	25,75
14	0,31	67,25	26,31
15	0,31	63,95	25,18
16	0,30	66,75	26,10
17	0,32	65,90	25,88
18	0,31	68,10	26,64
19	0,31	64,50	26,38
20	0,30	66,60	28,45
Mean	0,31	65,94	26,22
Maximum	0,32	73,53	29,31
Standard Deviation	0,00887	3,41	1,43
CV (%)	2,87	5,17	5,47

The evaluation of the tensile properties of the warp yarns showed that the maximum force values of the samples were relatively close to each other. This indicates that the warp yarns have similar strength against tensile forces. This result suggests that the yarn structure is generally uniform.

Table 4: Tensile Properties of Weft Yarns

Sample Code	Maximum Force (N)	Elongation at Break (mm)	Elongation at Maximum Force (%)
1	0,31	71,75	28,60
2	0,31	65,61	26,15
3	0,31	71,03	28,31
4	0,32	67,20	26,77
5	0,31	63,42	25,10
6	0,31	67,62	26,79
7	0,32	64,27	25,60
8	0,31	65,62	25,98
9	0,31	65,62	24,95
10	0,32	68,13	26,98
11	0,31	66,40	26,42
12	0,31	67,10	26,70
13	0,32	68,30	27,12
14	0,31	65,85	26,20
15	0,31	66,95	26,55
16	0,32	67,80	26,88
17	0,31	64,90	25,82
18	0,31	66,25	26,34

19	0,32	68,50	27,05
20	0,31	65,40	26,08
Mean	0,31	66,84	26,52
Maximum	0,32	71,75	28,60
Standard Deviation	0,005	2,46	0,96
CV (%)	1,61	3,68	3,62

The tensile test results of the weft yarns showed that the maximum force values of the samples were very similar. This indicates that the weft yarns have similar strength against tensile forces. The results suggest that the weft yarns show a generally uniform structural behaviour.

2.3 Pilling/Martindale Test Results

The pilling resistance of the fabric sample was performed according to ISO 12945-2 using the Martindale method. Following the Martindale test, the fabric sample was evaluated under a light cabinet using a pilling scale. Visual inspection revealed that the pilling degree of the sample was in the range of 4–5. This value indicates that there is negligible pilling and fuzzing on the fabric surface. No significant pilling formation was observed on the fabric surface after the test. Furthermore, no adverse conditions such as elastomer shedding, fraying, or surface deterioration were detected. This result shows that the plain weave fabric with 90% PES / 10% elastane exhibits good surface performance against friction. A pilling degree between 4–5 suggests that the fabric can largely maintain its surface appearance during use. Therefore, the Martindale test result was deemed positive, and the examined fabric sample was evaluated as having a very low tendency to pill.

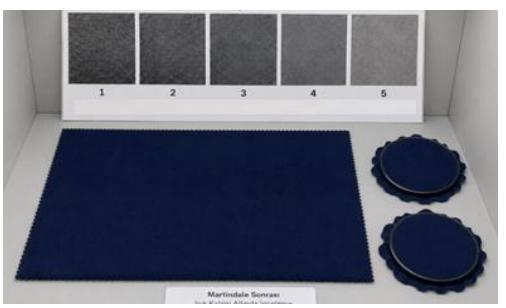

Figure 4: Martindale Test Results

2.4 Air Permeability Properties of the Fabric

The air permeability test was performed according to ISO 9237. During the measurements, a pressure difference of 25 Pa was applied to the fabric sample, and the average air permeability value was determined as 6 L/min.

2.5 Colour Properties of the Fabric

The measurements were performed using a Datacolor SF 600+ reflectance spectrophotometer. As a result of the measurements, the CIELAB colour coordinates (L*, a*, and b*) of the fabric were obtained.

Table 5: Colour Measurement Results of the Fabric Sample

Sample	L*	a*	b*	C*	h	X	Y	Z	x	y
Uniform Fabric	20,65	4,75	16,24	16,92	286,31	3,27	3,15	6,72	0,25	0,24

The L value of 20.65 indicates that the fabric has a dark colour appearance. The positive a value shows that the colour is slightly closer to the red axis, while the negative b* value indicates that the colour is located towards the blue axis. Based on these results, the sample was evaluated as having a dark blue/navy colour characteristic. The C* value represents the colour saturation, while the h value provides information about the colour hue angle.

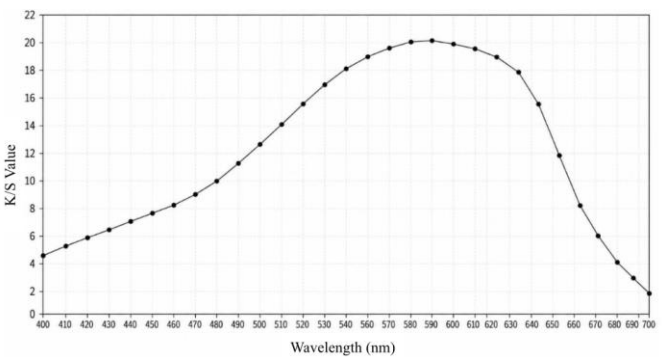

Figure 5: K/S Spectral Analysis of the Fabric Sample

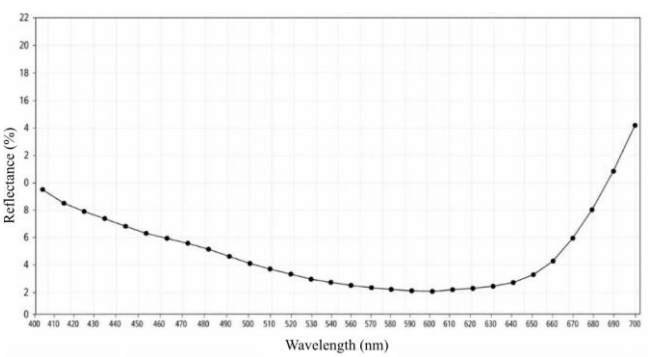

Figure 6: Spectral Reflectance Curve of the Fabric Sample

Examination of the curve shows that the fabric reflects light at different wavelengths. The reflectance values decrease from 400 nm onwards, reach their lowest level in the approximately 590–600 nm range, and then increase again. This indicates that the fabric absorbs more light at certain wavelengths and consequently exhibits a darker color character. The low reflectance values observed in the spectral reflectance curve indicate that the fabric absorbs a significant amount of light. This result is consistent with the low L* value obtained in the CIELab color measurement and supports the dark blue/navy color character of the fabric.

2.6 Evaluation of Colour Fastness to Laundering

The colour fastness to laundering test was carried out according to ISO 105-C06. The colour change of the sample and the staining on the multifibre fabric were assessed using the grey scale.

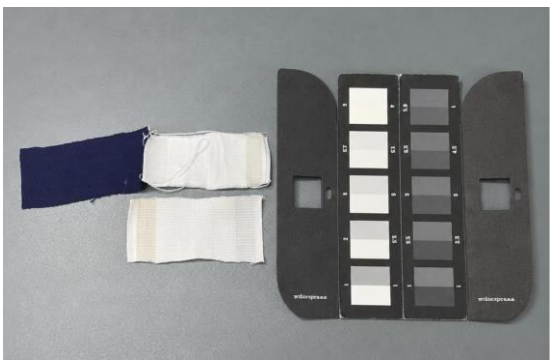

Figure 7: Grey Scale Evaluation of the Sample and Multifibre Fabric After Laundering

According to the gray scale evaluation, the laundering fastness result of the sample can be said to be at a good level. In particular, the absence of significant fading in the blue fabric and the lack of noticeable staining on the multifiber surface indicate that the fabric shows positive color retention against laundering conditions.

2.7 Dry and Wet Rubbing Fastness

Colour fastness testing was performed according to the ISO 105-X12:2016 standard. Both dry rubbing and wet rubbing tests were applied to the sample. The evaluation revealed colour fastness values of 4 for both dry and wet rubbing. This value indicates that very little colour transfer occurred onto the cotton rubbing cloth. Overall, the fabric sample showed good rubbing fastness performance.

2.8 Evaluation of Test Results Provided by Dressbest

The sample was subjected to a pilling resistance test at 2000 revolutions using the Martindale method. The pilling rating was determined as 5, and the fuzzing rating was also determined as 5. According to the evaluation scale, a rating of 5 indicates that no visible

change occurred on the fabric surface. These results indicate that the fabric sample has a very low tendency to pilling and fuzz formation under friction conditions. Obtaining pilling and fuzzing ratings of 5 after 2000 revolutions shows that the fabric maintains its surface appearance and exhibits high resistance to pilling during use. According to the report provided by Dressbest, the pH value of the fabric sample was determined as 7.11 according to the ISO 3071 standard. The reference range in the report is given as 4.5–7.5, and it is seen that the obtained pH value remains within this range. Therefore, the pH test result was evaluated as “PASS”. In the laundering fastness test, the sample and multifiber fabric were examined under a light cabinet with a gray scale, and no significant change in fabric color and no intense staining on the multifiber were observed. In this respect, the company's test result and the observational evaluation obtained in the university laboratory are consistent with each other. According to the test report provided by DressBest, the results for colour fastness to water, acidic perspiration, and alkaline perspiration were found to be in the range of 4 to 4/5. These findings indicate that the fabric does not show significant colour fading under wet use conditions and does not cause considerable dye transfer onto different fibre surfaces. The PASS results obtained in all three evaluations demonstrate that the sample has sufficient colour resistance against water and perspiration effects. The dimensional stability test after steaming showed that the fabric sample had a dimensional change of -1% in the warp direction and -2% in the weft direction. Since both values remained within the reference limit of ±3%, the test result was evaluated as PASS. These results indicate that the fabric maintained an acceptable dimensional stability after steam exposure and did not show significant shrinkage or loss of shape.

3. CONCLUSION

In this study, a plain weave fabric sample containing 90% polyester and 10% elastane was evaluated in terms of its physical properties, tensile behaviour, surface appearance, colour characteristics, and fastness performance. When the tests conducted in the university laboratory and the test results provided by DressBest were evaluated together, it was observed that the investigated fabric showed generally acceptable performance and suitability for use. The fabric weight, thickness, warp and weft density, air permeability, and tensile properties revealed the structural characteristics of the fabric, while the colour measurements and fastness tests supported that the fabric had an acceptable performance under usage conditions. In terms of surface performance, no significant elastane protrusion or severe surface damage was observed. However, it was concluded that the elastane protrusion problem is not only associated with the structural properties of the fabric but may also vary depending on user-related factors such as the application area of the product, frequency of use, areas exposed to friction, washing, and care conditions. Therefore, although laboratory test results are important indicators for the quality evaluation of elastane-containing fabrics, actual usage conditions of the product should also be taken into consideration.

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USAGE OF TEXTILE MATERIALS IN THE PACKAGING INDUSTRY

Review paper
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ABSTRACT: *Textile materials represent an important category of packaging materials due to their flexibility, durability, low weight, and adaptability to various packaging requirements. Although paper, plastic, metal, and glass dominate modern packaging markets, textile-based packaging continues to play a significant role in industrial, agricultural, transportation, luxury, and reusable packaging systems. Recent developments in technical textiles, smart textiles, digital printing technologies, and sustainable materials have further expanded the application potential of textile packaging. This paper provides an overview of textile materials used in packaging, their applications, imaging and decoration technologies, future technological trends and environmental aspects. The paper highlights the growing importance of sustainable textile packaging solutions within circular economy frameworks.*

Keywords: *Textile materials, applications, imaging Technologies, sustainability, future trends.*

UPOTREBA TEKSTILNIH MATERIJALA U INDUSTRIJI AMBALAŽE

APSTRAKT: *Tekstilni materijali predstavljaju značajnu kategoriju ambalažnih materijala zahvaljujući svojoj fleksibilnosti, izdržljivosti, maloj masi i prilagodljivosti različitim zahtevima pakovanja. Iako papir, plastika, metal i staklo dominiraju savremenim tržištem ambalaže, ambalaža zasnovana na tekstilnim materijalima i dalje ima važnu ulogu u industrijskim, poljoprivrednim, transportnim, luksuznim i višekratno upotrebljivim sistemima pakovanja. Nedavni razvoj tehničkih tekstila, pametnih tekstila, tehnologija digitalne štampe i održivih materijala dodatno je proširio potencijal primene tekstilne ambalaže. Ovaj rad pruža pregled tekstilnih materijala koji se koriste u ambalaži, njihovih primena, tehnologija oslikavanja i dekoracije, ekoloških aspekata, kao i budućih*

tehnoloških trendova. Rad takođe ukazuje na rastući značaj održivih rešenja za tekstilnu ambalažu u okviru koncepta cirkularne ekonomije.

Ključne reči: *Tekstilni materijali, primene, tehnologije oslikavanja, održivost, budući trendovi.*

1. INTRODUCTION

Packaging has evolved from a simple means of containing and transporting goods into a multidisciplinary field that combines engineering, materials science, marketing, sustainability, and consumer psychology. Throughout human history, the selection of packaging materials has been influenced by the need to protect products from environmental factors while simultaneously facilitating storage, transportation, and trade. While materials such as paper, plastics, metals, and glass dominate contemporary packaging markets, textile materials have maintained a unique and enduring role due to their versatility, flexibility, and adaptability to a wide range of products and distribution systems.

Textile packaging materials may be defined as flexible structures produced from fibers, yarns, fabrics, or nonwoven materials designed to contain, protect, transport, or present products. Textile materials have been used for packaging since ancient times, when natural fibers were used to produce sacks, bags, and wrapping materials [1]. Although industrialization introduced alternative materials with greater barrier properties and lower production costs, textile packaging continued to evolve rather than disappear. Today, textile materials are widely employed in applications ranging from bulk industrial packaging and agricultural transport systems to luxury product presentation and reusable consumer packaging.

The increasing global focus on sustainability has renewed interest in textile packaging solutions. Consumers, governments, and manufacturers are actively seeking alternatives to single-use packaging materials, particularly plastics that contribute to environmental pollution and resource depletion. Textile materials, especially those derived from renewable natural fibers or recycled sources, offer promising opportunities for reducing the environmental footprint of packaging systems. At the same time, advances in textile engineering have led to the development of highly specialized technical textiles capable of providing sophisticated functional properties.

Understanding the variety of textile materials available for packaging applications is therefore essential for packaging designers, manufacturers, and researchers. This chapter provides an overview of the principal textile materials used in packaging, their classifications, and the properties that make them suitable for specific packaging functions. Packaging materials serve multiple functions including protection, transportation, storage, communication, and marketing. Among the broad range of packaging materials, textiles occupy a specialized but increasingly important position due to their unique mechanical and functional properties [2].

1.1. Classification of textile materials according to fiber origin

Modern textile packaging materials can be divided by fiber origin to natural and synthetic textile materials fiber. Natural fibers remain widely used due to their biodegradability and renewable origin. Some of the most used are cotton, jute, hemp and flax. Cotton fabrics provide softness, flexibility, and excellent printability. They are commonly used for luxury packaging, reusable shopping bags, promotional packaging, and food packaging applications [3]. Jute is one of the most widely used packaging fibers due to its high tensile strength, low cost, and biodegradability. Jute sacks are commonly employed for agricultural products such as coffee, cocoa, rice, and grains [4]. Hemp fibers exhibit excellent mechanical properties and environmental performance. Hemp-based packaging materials have gained attention as sustainable alternatives to synthetic textile packaging [5]. Flax fibers provide good strength-to-weight ratios and are increasingly used in premium packaging applications.

Synthetic fibers dominate industrial packaging because of their durability and resistance to environmental factors. Polypropylene is the most important synthetic textile material used in packaging. Woven polypropylene fabrics are extensively used for bulk bags, fertilizer sacks, cement bags, and industrial packaging [6]. Polyester textiles offer excellent dimensional stability, UV resistance, and mechanical performance. They are frequently used in transport packaging and protective packaging systems. Polyamide materials provide high abrasion resistance and durability, making them suitable for reusable industrial packaging.

Technical textiles represent one of the fastest-growing sectors of textile packaging. These materials are engineered to provide specific performance characteristics such as:

- Barrier properties
- Antimicrobial activity
- Moisture control
- Thermal insulation
- Impact protection

Technical textile packaging is widely used in pharmaceuticals, electronics, food logistics, and high-value industrial products [7].

1.2. Classification of Textile Materials According to Structural Formation

Textile materials can be classified according to their structural formation method into woven, knitted, nonwoven, and several other specialized textile structures such as braided, netted, and felted materials. The fundamental difference between these categories lies in the way fibers or yarns are assembled into a textile structure, which directly influences their mechanical, physical, and functional properties.

Woven fabrics are produced by the perpendicular interlacement of two sets of yarns. Woven textiles are suitable for applications requiring structural integrity, such as industrial packaging sacks, geotextiles, composite reinforcements, and transport packaging.

Because the yarns are tightly interlaced, woven fabrics generally exhibit high tensile strength, good dimensional stability and high durability under mechanical loads

Knitted fabrics are formed by interlooping yarns into a series of interconnected loops. Due to their flexibility, knitted textiles are commonly used in apparel, technical textiles, protective covers, cushioning materials, and specialized packaging applications where adaptability to irregular shapes is required. The looped architecture gives knitted fabrics high elasticity and stretchability and higher air permeability.
Nonwoven fabrics are produced directly from fibers rather than yarns. Fibers are arranged into a web and subsequently bonded through mechanical, thermal, or chemical processes. Key characteristics of nonwoven materials include low production cost adjustable porosity and lightweight structure.
However, nonwovens generally exhibit lower durability and mechanical strength than woven textiles unless specifically engineered for high-performance applications. They are widely used in filtration systems, medical products, hygiene products, protective packaging, agricultural coverings, and shopping bags.
Braided textiles are produced by the diagonal intertwining of three or more yarn systems, following helical paths around a central axis. Braided materials provide excellent flexibility, resistance to torsion, and load distribution. They are commonly used in ropes, cords, reinforcement structures, and composite materials.
Felted materials are among the oldest textile structures and are formed through the mechanical entanglement of fibers in nonorganized yarn structure, often aided by heat, moisture, and pressure. Felt exhibits good thermal insulation, vibration damping, and cushioning properties.
Netted textiles consist of yarns interconnected to create open structures with large pores. These materials provide excellent ventilation, low weight, and flexibility. In packaging applications, netted textiles are frequently used for agricultural products such as fruits, vegetables, and seafood, where airflow is essential for product preservation.

2. APPLICATIONS OF TEXTILE MATERIALS IN THE PACKAGING INDUSTRY

The effectiveness of any packaging material is ultimately determined by its ability to satisfy the functional requirements of specific products, supply chains, and consumer expectations. Their unique combination of flexibility, durability, low weight, and reusability allows textile materials to occupy niches that cannot always be efficiently served by rigid packaging alternatives.
In recent decades, globalization has transformed supply chains, increasing the distances that products travel between production facilities, distribution centers, retailers, and consumers. As a result, packaging systems must provide not only protection but also logistical efficiency, sustainability, and cost-effectiveness. Textile packaging solutions have responded to these challenges by offering lightweight structures with excellent strength-to-weight ratios, reducing transportation costs while maintaining product safety.
At the same time, changing consumer attitudes toward sustainability have contributed to the growing popularity of reusable textile packaging. Reusable shopping bags, fabric gift packaging, and textile-based premium packaging have become symbols of

environmentally responsible consumption. Beyond their functional role, textile materials can also enhance the sensory and emotional experience associated with a product, contributing to perceptions of quality, authenticity, and value.

The diversity of textile packaging applications reflects the diversity of textile materials themselves. Different fibers, fabric constructions, and manufacturing technologies enable textile packaging solutions to be tailored for highly specific requirements.

Textile materials are employed across numerous packaging sectors due to their versatility and functional performance. Agricultural products remain among the largest consumers of textile packaging such as sacks and bags. Jute and polypropylene woven sacks dominate this sector because they provide ventilation while maintaining mechanical strength [4].

Flexible Intermediate Bulk Containers (FIBCs), commonly known as bulk bags or "big bags," represent one of the most important industrial textile packaging applications. FIBCs are typically manufactured from woven polypropylene and can carry loads ranging from 500 kg to over 2000 kg [6].

Textile materials are increasingly utilized in food packaging due to consumer demand for natural and reusable packaging solutions. Cotton and linen packaging are especially popular in premium food markets.

Luxury brands frequently employ textile materials to enhance perceived value and customer experience. Textile packaging contributes to perceived quality, exclusivity, and sustainability [8]. Common applications include jewelry pouches, premium alcohol, fashion and cosmetic packaging.

Textile materials provide cushioning and protection during transportation, nonwoven fabrics and spacer textiles are particularly effective for impact protection. They often used for protection of electronic devices, glass products and automotive components.

Growing environmental concerns have driven widespread adoption of textile shopping bags reusable textile bags significantly reduce single-use packaging waste [9].

3. IMAGING AND DECORATION TECHNOLOGIES FOR TEXTILE PACKAGING

Packaging serves not only as a protective container but also as a powerful communication medium. In highly competitive markets, the visual appearance of packaging frequently influences consumer perceptions, product differentiation, brand recognition, and purchasing decisions. The ability to apply graphics, text, symbols, and decorative elements to packaging materials is therefore a critical aspect of packaging design and production. Textile packaging is no exception; in fact, the inherent tactile and visual characteristics of textile materials often provide unique opportunities for creating distinctive packaging experiences. Modern textile packaging can incorporate high-resolution graphics, personalized content, interactive digital features, and sophisticated decorative effects that rival or exceed those available on conventional packaging materials.

As packaging increasingly functions as both a physical and digital interface between brands and consumers, understanding the available imaging and decoration technologies becomes

essential. Visual communication is a critical function of packaging. Textile packaging employs a variety of imaging and decoration technologies.
Screen printing remains one of the most widely used techniques for textile packaging. The technology is particularly common in reusable shopping bags and promotional packaging (Ujiie, 2006). Screen printing offers high ink opacity, durability and compatibility with various fabrics.
Flexographic printing is used for high-volume textile packaging production. Flexography is frequently employed for industrial sacks and bulk packaging. It offers high productivity and cost efficiency.
Digital printing has transformed textile packaging production. Inkjet technologies enable high-resolution graphics directly onto textile surfaces [10]. Benefits include short production runs, personalization, rapid prototyping, reduced waste.
Dye sublimation allows permanent color transfer onto polyester-based textile materials. The technology is widely used for promotional textile packaging as it offers excellent color reproduction and high image quality
Heat transfer systems enable application of pre-printed graphics to textile substrates. This method is suitable for limited production runs, customized packaging, promotional products.
Embroidery provides premium visual and tactile qualities needed for luxury packaging, corporate gifts packaging and high-end textile pouches as it enhances perceived product value and craftsmanship.
Laser technologies have gained importance in textile packaging decoration with surface engraving, pattern generation and variable data marking.
Smart printing technologies are encompassing recent innovations such as conductive inks, NFC-enabled textiles, QR code integration, interactive packaging surfaces. These technologies enable traceability and enhanced consumer engagement.

4. FUTURE TRENDS AND ECOLOGICAL ASPECTS OF TEXTILE PACKAGING

The packaging industry is currently undergoing one of the most significant periods of technological transformation in its history. Driven by advances in material science, digitalization, automation, and sustainability initiatives, packaging systems are becoming increasingly intelligent, functional, and environmentally responsible. Textile packaging is actively participating in this transformation, benefiting from innovations that are expanding both its capabilities and its range of applications.
Several global trends are influencing the future development of textile packaging. Consumers increasingly demand sustainable products and environmentally responsible packaging solutions. Simultaneously, manufacturers seek packaging materials that offer enhanced performance, improved supply chain visibility, and greater opportunities for product differentiation. Technological developments in smart materials, nanotechnology, additive manufacturing, and digital communication are enabling packaging systems to perform functions that were previously unimaginable.

The convergence of textile engineering with electronics and information technologies is particularly noteworthy. Smart textile packaging systems capable of monitoring environmental conditions, tracking products throughout supply chains, and communicating information directly to consumers are rapidly moving from research laboratories into commercial applications. In parallel, bio-based and biodegradable textile materials are being developed to address growing environmental concerns and regulatory pressures.
Understanding these emerging technologies is important not only for researchers but also for designers, manufacturers, and policymakers seeking to anticipate future developments in packaging systems.
The textile packaging sector is undergoing rapid technological transformation. Integration of electronics into textile packaging represents a significant innovation area [11]. Smart textiles incorporate sensing and communication functions. Future applications predict temperature monitoring, freshness indicators, anti-counterfeiting systems, supply chain tracking, etc.
Nanomaterials and advanced coatings in the future can enhance barrier performance, antimicrobial properties, UV resistance, mechanical strength and it is expected to play an increasingly important role in advanced textile packaging systems. These functionalities expand the applicability of textile packaging in food and pharmaceutical sectors.
Industry 4.0 technologies are reshaping textile packaging production with digital textile printing, automated cutting systems, artificial intelligence quality control and additive manufacturing integration. These developments improve flexibility, customization, and production efficiency.
Environmental sustainability has become one of the most influential factors shaping the future of the global packaging industry. Growing concerns regarding climate change, resource depletion, waste generation, and plastic pollution have intensified pressure on manufacturers to develop packaging systems that minimize environmental impacts while maintaining functional performance. The environmental performance of packaging materials depends on numerous factors, including raw material extraction, manufacturing processes, transportation requirements, product lifespan, reuse potential, and end-of-life management. Textile materials present both opportunities and challenges in relation to these factors. Textile packaging offers several environmental benefits: reusability, durability, long service life, reduced waste generation, potential biodegradability. Recycled textile fibers from post-consumer textiles, PET bottle recycling, industrial textile waste are increasingly utilized in packaging applications. This reduces raw material consumption and landfill disposal. Reusable textile bags can significantly reduce environmental impacts compared with disposable alternatives [9].
Circular economy approaches and modern packaging strategies emphasize design for reuse, design for recycling material recovery, closed-loop manufacturing. Future packaging systems will combine reusable textile structures, digital identification, material tracking and automated recycling infrastructure. Such systems will support sustainable supply chains and resource efficiency. Textile packaging is particularly suitable for circular business models because of its durability and repairability. Natural fibers are biodegradable and originate from renewable resources. These materials align well with circular economy

principles. Lifecycle assessment studies indicate that sustainability performance depends heavily on reuse frequency and end-of-life management [12].
Bio-based fibers research focuses on developing packaging textiles from bamboo fibers, agricultural waste, cellulose nanofibers and mycelium-based materials. These materials offer improved sustainability and reduced environmental impacts.
Given the complexity of sustainability assessment, a comprehensive understanding of both the benefits and limitations of textile packaging is necessary. Despite their benefits, textile packaging materials face several environmental concerns such as water-intensive cotton production, synthetic fiber microplastic pollution, dyeing-related environmental impacts and transportation emissions.

6. CONCLUSION

Packaging systems are continuously evolving in response to technological innovation, changing consumer expectations, and increasing environmental challenges. Throughout this evolution, textile materials have demonstrated remarkable resilience and adaptability, maintaining their relevance despite competition from alternative packaging materials. Their unique combination of flexibility, durability, reusability, and aesthetic qualities enables textile materials to serve a wide variety of packaging functions that extend far beyond their traditional applications.
The preceding chapters have shown that textile packaging encompasses a diverse range of materials, technologies, and industrial applications. From natural fibers used in agricultural packaging to advanced technical textiles employed in high-performance logistics systems, textile materials continue to contribute significantly to modern packaging solutions. Advances in imaging technologies, sustainability practices, and smart packaging systems are further enhancing their value and expanding their application potential.
As the packaging industry moves toward greater sustainability, digital integration, and circular economy models, textile materials are likely to play an increasingly important role. Continued research and technological innovation will be essential for overcoming existing limitations and unlocking new opportunities for textile-based packaging. The future of textile packaging will depend not only on improvements in material performance but also on its ability to contribute to broader economic, environmental, and social sustainability objectives.

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MULTI-FUNCTIONAL RADIATIVE COOLING CURTAIN FABRIC WITH FLAME-RETARDANT AND SELF-CLEANING FUNCTIONS

Scientific paper
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ABSTRACT: *Today, the development of functional curtain materials to promote building energy efficiency is highly demanded because of the effects of global warming and limits about natural sources. At this point, treating curtain materials with passive radiative cooling materials by different methods is valuable in thermal management of indoor environments. Besides thermal management performance, other functions such as self-cleaning and flame retardancy, which have been studied for longer periods, are crucial for building textile components. To address the mentioned requirements, a superhydrophobic passive cooling fabric was designed through a finishing treatment consisting of polyvinylidene fluoride (PVDF)-silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and Al_2O_3@SiO_2 on a standard polyester curtain fabric. The required porous structure was enabled by solvent exchange phase separation method and a spray-dry procedure was used considering scalability and environmental concerns. Besides chemical and morphological analyses with FT-IR and SEM, passive cooling performance of the fabrics were determined indirectly by sphere-integrated FT-IR and UV-VIS spectrophotometers and directly by a designed hotplate system with a sun simulator. Results show that the nanocomposite treatments, especially the one including binary Al_2O_3@SiO_2 particles enabled a passive cooling performance up to 7.38°C compared to the raw fabric as a result of its enhanced solar reflectivity and infrared emissivity depending on the nanoparticles used and micro-nano multi-stage porous structure. Moreover, nanocomposite treated fabrics endow sufficient self-cleaning and flame-retardant performances as based on intrinsic characteristics of the nanocomposite materials. It can be concluded that, building textile components such as curtains can be functionalized as radiative passive coolers besides the garment systems to contribute economy and energy efficiency components of sustainability.*

Keywords: *Radiative cooling, curtain fabric, thermal management, energy efficiency.*

VIŠENAMENSKA TKANINA ZA ZAVESE ZA RADIJACIJU SA FUNKCIJAMA OTPORNOSTI NA VATRA I SAMOČIŠĆENJA

APSTRAKT: *Danas je razvoj funkcionalnih materijala za zavese radi promocije energetske efikasnosti zgrada veoma tražen zbog efekata globalnog zagrevanja i ograničenja prirodnih izvora. U ovom trenutku, tretiranje materijala za zavese pasivnim materijalima za zračenje različitim metodama je vredno u termičkom upravljanju unutrašnjim okruženjima. Pored performansi termičkog upravljanja, druge funkcije kao što su samočišćenje i otpornost na plamen, koje se proučavaju duže vreme, ključne su za tekstilne komponente zgrada. Da bi se zadovoljili pomenuti zahtevi, dizajnirana je superhidrofobna pasivna tkanina za hlađenje završnom obradom koja se sastoji od polivinilidenfluorida (PVDF)-silicijum dioksida (SiO2), aluminijum oksida (Al2O3) i Al2O3@SiO2 na standardnoj poliesterskoj tkanini za zavese. Potrebna porozna struktura je omogućena metodom fazne razdvojenosti izmenom rastvarača, a korišćen je postupak sušenja raspršivanjem uzimajući u obzir skalabilnost i ekološke probleme. Pored hemijskih i morfoloških analiza pomoću FT-IR i SEM, performanse pasivnog hlađenja tkanina su indirektno određene pomoću sferno integrisanih FT-IR i UV-VIS spektrofotometara i direktno pomoću dizajniranog sistema grejne ploče sa simulatorom sunca. Rezultati pokazuju da su nanokompozitni tretmani, posebno onaj koji uključuje binarne Al2O3@SiO2 čestice, omogućili performanse pasivnog hlađenja do 7,38°C u poređenju sa sirovim materijalom kao rezultat njegove poboljšane reflektivnosti sunčevog zračenja i infracrvene emisivnosti u zavisnosti od korišćenih nanočestica i mikro-nano višestepene porozne strukture. Štaviše, tkanine tretirane nanokompozitom imaju dovoljne performanse samočišćenja i usporavanja plamena na osnovu suštinskih karakteristika nanokompozitnih materijala. Može se zaključiti da se komponente građevinskog tekstila, kao što su zavese, mogu funkcionalizovati kao radijativni pasivni hladnjaci pored sistema odeće kako bi doprinele ekonomiji i energetskoj efikasnosti komponenti održivosti.*

Ključne reči: *Radijativno hlađenje, tkanina za zavese, upravljanje toplotom, energetska efikasnost.*

1. INTRODUCTION

As heat stress triggered by global warming becomes a serious health issue threatening billions of people worldwide, the high energy consumption and greenhouse gas emissions of traditional air conditioning methods make the search for urgent solutions imperative for passive, energy-efficient thermal management solutions. According to annual reports, more than 30% of global final energy consumption used in buildings and also approximately 20% of global carbon emissions [1-4]. Therefore, passive thermal management systems that can reduce heat gain without external energy input have attracted considerable attention in recent years. Among these approaches, passive daytime radiative cooling (PDRC) has emerged as a promising strategy for building thermal management due to its ability to dissipate heat to outer space through the atmospheric transparency window (8-13 μm) while simultaneously minimizing solar heat absorption [5]. The main focus of PDRC materials for buildings is the fabrication of building envelope materials, exterior building coatings, wall, roof, greenhouse cover, and smart windows [6].

Besides wearable applications, building textiles such as curtains, awnings, and shading systems have recently emerged as attractive candidates for passive cooling applications because they directly influence indoor solar heat gain and thermal comfort [7]. Curtain fabrics are particularly important due to their large surface area and direct exposure to solar radiation through windows. Curtain fabrics are particularly important due to their large surface area and direct exposure to solar radiation through windows. Functionalization of curtain textiles with radiative cooling materials can therefore contribute to building energy efficiency by reducing indoor heat accumulation. As interior elements that directly interact with incoming solar radiation, curtains can contribute significantly to reducing indoor thermal loads when designed with appropriate optical properties, namely high solar reflectance in the 0.3-2.5 μm range and high mid-infrared emissivity in the 8-13 μm atmospheric window. While recent studies have demonstrated the feasibility of passive radiative cooling in curtains [5], the application of such coatings specifically to curtain fabrics remains limited as compared with wearable cooling textiles, particularly when multifunctionality is considered. In one of the few studies about this subject, passive cooling curtain was developed by applying a porous SiO_2/poly(vinylidene fluoride-hexafluoropropylene) composite coating onto the cotton by solvent exchange phase separation and sanding techniques. Although, an efficient outdoor cooling performance was obtained with an average of 10.3°C temperature drop as compared to the refence ones based on porous structure, low thermal conductivity, high solar reflectance and infrared emittance, flame-retardant capability has not been investigated [5]. On the other hand, additional functionalities such as flame retardancy and self-cleaning behavior are also essential for building textile applications in terms of safety, durability, and long-term performance preservation besides thermal management performance.

Among various radiative cooling materials, PVDF has attracted considerable attention owing to its intrinsic infrared emissivity, chemical stability, and processability for porous structure formation [8]. Furthermore, ceramic nanoparticles such as SiO_2 and Al_2O_3 are widely utilized to improve solar reflectance due to their strong light scattering capability and high refractive index contrast [9]. Especially, hierarchical porous structures combined with inorganic nanoparticles can enhance broadband Mie scattering across the solar spectrum while simultaneously increasing mid-infrared emission characteristics. Recent studies reported that binary or hybrid nanoparticle systems could generate synergistic optical effects, leading to improved passive cooling efficiency compared to single-particle systems [9].

In this study, multifunctional passive radiative cooling curtain fabrics were developed through porous PVDF-based nanocomposite coatings including SiO_2, Al_2O_3, and binary Al_2O_3@SiO_2 nanoparticles using a solvent exchange phase separation and spray-coating method considering scalability and environmental concerns. In addition to passive cooling capability, flame-retardant and self-cleaning performances of the treated fabrics were also investigated to obtain multifunctional building textile materials suitable for practical applications.

2. MATERIALS and METHODS

2.1. Materials

A 100% polyester curtain fabric with a weight of 220 g/m² and a thickness of 0.4 mm, supplied by Berteks Tekstil (Bursa, Türkiye), was used as the substrate. For developing composite finishing treatment, PVDF (Kynar® 721, melting temperature: 168°C, glass transition temperature: -40°C) as matrix material, was kindly provided from Arkema, France. SiO_2 (12-23 nm) (Nanografi, Türkiye), Al_2O_3 (4 nm) (Nanografi, Türkiye) were used as nanofiller. To develop porous structure, binary solvents were N, N dimethyl acetamide (Sigma Aldrich, DMAc) and acetone (Acros Organics, ACE) and non-solvent component was deionized water used in solvent exchange phase separation method. Dispersion of nanoparticles in the polymer matrix was obtained with using non-ionic surfactant (sorbitan monostearate, Span60, Sigma Aldrich) during ultrasonic bath mixing.

2.2. Methods

2.2.1. Preparation of porous coated curtain fabrics

For developing heterogeneous porous nanocomposite structures on fabric surface by solvent exchange phase separation method, nanocomposite dispersions including SiO_2, Al_2O_3, and binary Al_2O_3@SiO_2 nanoparticles were sprayed on the fabric. Firstly, PVDF polymer chips at 10 wt. % were dissolved in a binary solvent system of DMAc and ACE (with a volume ratio of 1:1) at 50°C through mechanical stirring for 6 h. Subsequently, appropriate amounts of SiO_2, Al_2O_3, and binary Al_2O_3@SiO_2 (1:2 ratio) to get 2 wt. % particle content were sequentially added under continuous stirring, which was maintained for an additional 1 h. Also, non-ionic surfactant (Span60, with a particle/Span60 weight ratio of 1:2) was added into the dispersion to prevent particle agglomeration. To ensure homogeneous dispersion of the SiO_2, Al_2O_3, and binary Al_2O_3@SiO_2 nanoparticles within the PVDF polymer matrix, the solution underwent ultrasonication for 0.5 h. Subsequently, the prepared nanocomposite dispersions were applied onto the fabrics using a simple spraying system (Alfajet-W77S, Türkiye) at thickness of 200 µm. After 1 min, deionized water (50 mL) was sprayed on the coated surface and treated fabrics were dried at 20°C for 24 h. The obtained samples were coded as P_PVDF, P_SiO_2, P_Al_2O_3, and P_Al_2O_3@SiO_2, respectively.

2.2.2. Material characterization

The surface micro-morphology and porous structure of the raw and treated fabrics were characterized using scanning electron microscopy (SEM, ZEISS EVO LS10) at 250-1000 magnification. Chemical structures were determined using a Bruker VERTEX 70v Fourier transform infrared spectrometer (FT-IR) in ATR mode in the 400-4000 cm^{-1} range, 2 cm^{-1} resolution, and 16 scan at room temperature.

For determining spectral properties, reflectance ($\rho(\lambda)$) and transmittance ($\tau(\lambda)$) of the fabrics in the atmospheric window wavelength range (8-13 µm) were obtained using a FT-IR spectrometer (Bruker VERTEX 70v) having integrated sphere and the average emissivity values were calculated according to Equation (1) and Equation (2). According to Kirchhoff's Law, the spectral absorptivity is equal to emissivity when an object is in thermodynamic equilibrium.

$$\varepsilon(\lambda) = 1 - \rho(\lambda) - \tau(\lambda) \quad (1)$$

$$\bar{\varepsilon} = \frac{\int_{8\ \mu m}^{13\ \mu m} I_{BB}(\lambda,T)\varepsilon(\lambda)\mathrm{d}\lambda}{\int_{8\ \mu m}^{13\ \mu m} I_{BB}(\lambda,T)\mathrm{d}\lambda} \quad (2)$$

Also, the reflectance spectra of the fabrics in the sunlight band (0.3-2.5 μm) were recorded using a JASCO V-770 spectrophotometer equipped with an integrating sphere. The average solar reflectance was calculated according to Equations (3).

$$\bar{\rho}_{solar} = \frac{\int_{0.3\ \mu m}^{2.5\ \mu m} I_{solar}(\lambda)\cdot\rho(\lambda)\mathrm{d}\lambda}{\int_{0.3\ \mu m}^{2.5\mu m} I_{solar}(\lambda)\mathrm{d}\lambda} \quad (3)$$

where ε: emissivity, ρ: reflection, τ: transmittance, and λ: wavelength, $I_{solar}(\lambda)$: global solar intensity spectrum according to ASTM G173, I_{BB}: spectral radiance of a blackbody defined by Planck's law at temperature T.
A custom-designed device including 8 K-type thermocouple sensor probes, a sun simulator halogen lamp, and a data acquisition system, was used to figure out passive radiative cooling performance under simulated indoor condition. After 1 min stabilizing period, temperature data was monitored with 10 s frequency and recorded precisely for 20 min lamp-on and lamp-off stages, respectively. The average temperature variation on the lower surface of the sample were determined by performing least three replications for each sample. All tests were carried out under 500 W/m^2 solar irradiance.
Flame retardant performance of the raw and treated fabric was determined using a BV AFC Auto flame-retardant test apparatus in accordance with standard AATCC 6941. During the test, the combustion phenomena during burning and post combustion morphology were recorded using a 12 s ignition duration by 40 mm flame height.
Self-cleaning performance of the coated fabrics were determined by solid contaminant removal test under ambient condition. Soil was uniformly distributed on the surfaces of the fabrics, which were fixed at a specific inclination for simulating contamination. Deionized water was then applied onto the contaminated area for rinsing surface. Also surface wettability of the samples were determined by depositing three liquids (methyl blue dye in water, water, and coffee) on the surface.

3. RESULTS

In this study, radiative cooling curtain fabrics with flame-retardant and self-cleaning functions, were designed to reduce indoor and outdoor heat exchange, thus achieving energy-saving in building thermal management from the perspective of curtains. These radiative cooling curtain fabrics with flame-retardant and self-cleaning functions were obtained with applying PVDF-SiO_2, Al_2O_3, and Al_2O_3@SiO_2 on a standard polyester curtain fabric by solvent exchange phase separation method and a spray-dry procedure. SEM images of the raw fabric samples (Figure 1 (a, b)) exhibited a flat and smooth surface

appearance. Through PVDF and PVDF-Al_2O_3@SiO_2 finishing process, a micro-nano-porous and rough coating layer was observed on the fabric surface Figure 1 (c-f) due to phase separation resulting from the displacement of ACE first, followed by DMAc and water, depending on the evaporation rates of the mixture reaching the fabric surface [5]. As compared to the coated fabrics with only PVDF, Al_2O_3@SiO_2 particles are also visible on the fabric surface (Figure 1 (e, f)) with a micro-nano-porous and rough coating layer. The enhanced microstructure of the raw fabric (standard PET curtain) by porous coatings is expected to increase passive cooling performance of those fabrics through the higher solar reflection and infrared emission.

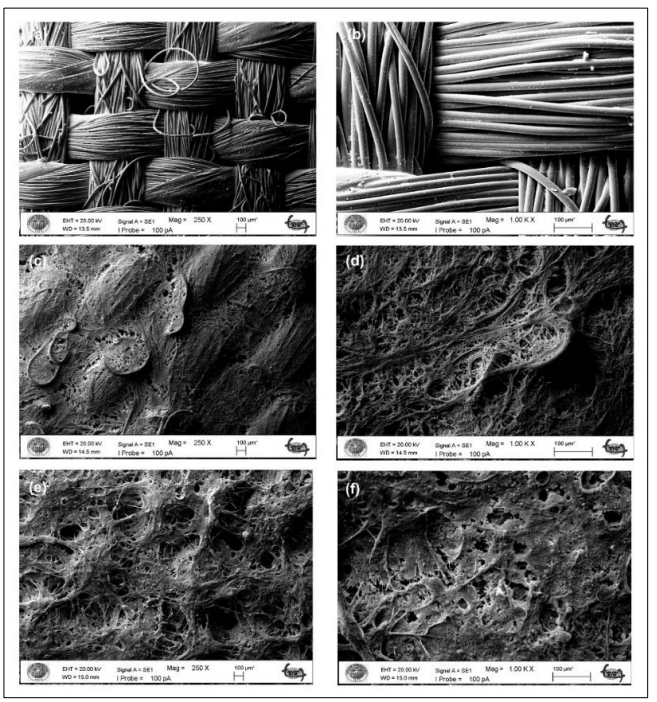

Figure 1: Surface SEM images of the raw (a, b), P_PVDF (c, d), and P_Al_2O_3@SiO_2 (e, f) fabrics at 250x and 1000x magnification

To further understand the chemical composition of the raw and treated fabrics were characterized by FT-IR analysis and infrared spectra were given in Figure 2. The raw fabric sample show characteristic peaks of polyester; C=O stretching band at 1714 cm^{-1}, aromatic ring stretching at 1409 cm^{-1}, C(=O)-O stretching at 1242 cm^{-1}, and aromatic bending bands at 1016 and 725 cm^{-1}. In the FT-IR spectra of all composite-treated fabrics (P_SiO_2, P_Al_2O_3, and P_Al_2O_3@SiO_2), characteristic C-F vibrations of the PVDF polymer [8] were detected at 1172, 881, and 838 cm^{-1}, respectively. In addition to these peaks, P_SiO_2 and P_Al_2O_3 samples exhibit intrinsic vibrational characteristic Al-O bond in 500-900 cm^{-1}

range and Si-O stretching vibrations at around 462 cm^{-1}, symmetric Si-O-Si bendings at 721 cm^{-1}, Si-O-Si asymmetric bending at 1070 cm^{-1}, providing the existence of SiO_2 and Al_2O_3 particles in the structure. Also, the presence of mentioned characteristic peaks of Al-O and Si-O-Si asymmetric bending as well as C-F vibrations in P_Al_2O_3@SiO_2 ones indicates that binary Al_2O_3@SiO_2 nanoparticles within the PVDF polymer matrix has been successfully integrated into the fabric structure. According to FT-IR spectra coated fabrics especially P_Al_2O_3@SiO_2 ones could possess high infrared emission characteristics in the atmospheric transparent window due to the mentioned molecular vibration peaks overlapping the atmospheric transparency window (8-13 µm) corresponded exactly to the absorption at 1250-780 cm^{-1}.

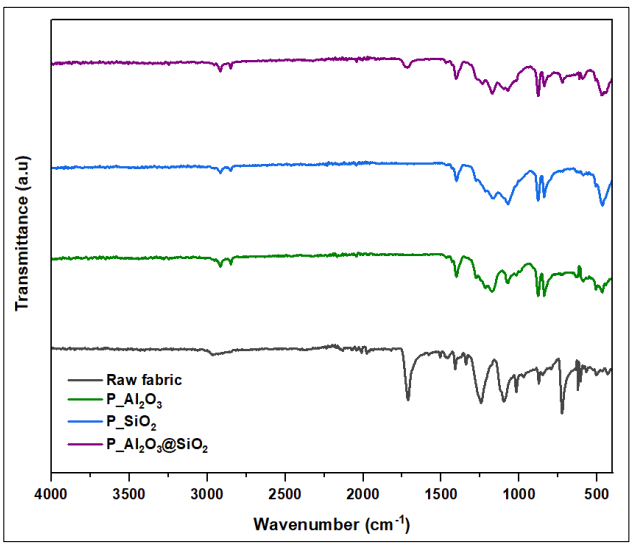

Figure 2: FT-IR spectra of the raw fabric, P_Al_2O_3, P_SiO_2, P_Al_2O_3@SiO_2 samples

For developing passive radiative cooling curtain, solar reflectance and infrared emission in corresponding wavelength which are crucial parameters, were measured and corresponding spectra were given in Figure 3 and Figure 4, respectively. As compared to the raw samples, coated samples especially ones including binary Al_2O_3@SiO_2 particles exhibited higher solar reflectance function. Also, it is observed that P_SiO_2 sample exhibit higher solar reflectance than samples including Al_2O_3 when the effect of particle type is evaluated. This can be attributed to broad-band scattering properties of SiO_2 particles [9]. The raw fabric had 47.73% average solar reflectance while P_SiO_2, P_Al_2O_3, and P_Al_2O_3@SiO_2 had average solar reflectance of 62.98, 67.16, and 77.64%, in turn. This was due to the micro-nano multi-stage porous structures of composite coatings on the fabric, which could have effectively enhanced the Mie scattering of sunlight and significantly reduced the sunlight energy absorption by the fabric. Also, the combination of Al_2O_3 and SiO_2 particles resulted in generation of multiple scattering effect spanning the entire solar spectrum.

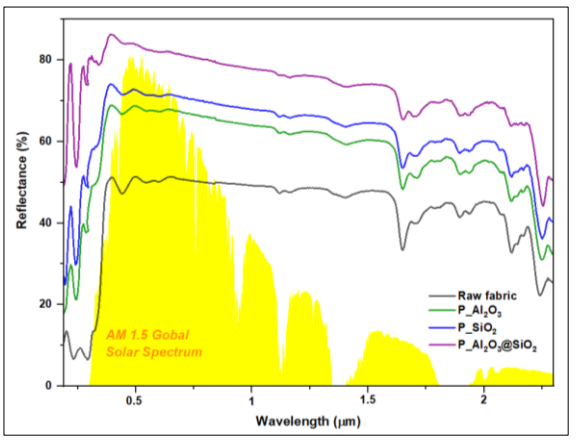

Figure 3: Solar reflectance spectra of the raw fabric, P_Al_2O_3, P_SiO_2, P_Al_2O_3@SiO_2 samples

Similarly, the average infrared emissivity of the coated samples specially including binary Al_2O_3@SiO_2 particles from in the atmospheric transparent window increased from 86.83% to 88.16% compared to the raw fabric samples. The infrared emission of the material is mainly determined by its internal functional groups. The synergetic absorption molecular vibration peaks of PVDF polymer with Al_2O_3 and SiO_2 particles in mid infrared region overlapping the atmospheric transparency window (8-13 μm) corresponded exactly to the absorption at 1250-780 cm^{-1}, may resulted in higher infrared emissivity values. In summary, coated fabrics especially with PVDF-Al_2O_3@SiO_2 ones are characterized by high solar reflectance and high infrared emission, which represent promising candidates for energy-efficient thermal management in buildings.

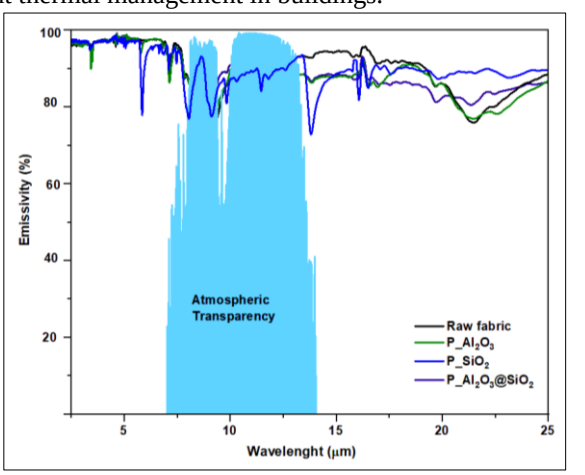

Figure 4: Infrared emission spectra of the raw fabric, P_Al_2O_3, P_SiO_2, P_Al_2O_3@SiO_2 samples

To demonstrate the passive cooling capability of the samples were measured by recording the real-time temperature using a designed hotplate system under under 500 W/m^2 simulated sunlight. As seen in Figure 5, P_Al_2O_3@SiO_2 samples had a temperature of 44.12°C, which is lower than coated samples with composite coating including Al_2O_3 and SiO_2 (46.34 and 46.73, respectively), PVDF ones (48.02°C) and the raw samples (51.5°C) under 500 W/m^2 solar irradiance. Furthermore, the maximum cooling performance was achieved in P_Al_2O_3@SiO_2 samples with 7.38°C temperature drop based higher solar reflectance and mid-infrared emittance as compared to raw ones.

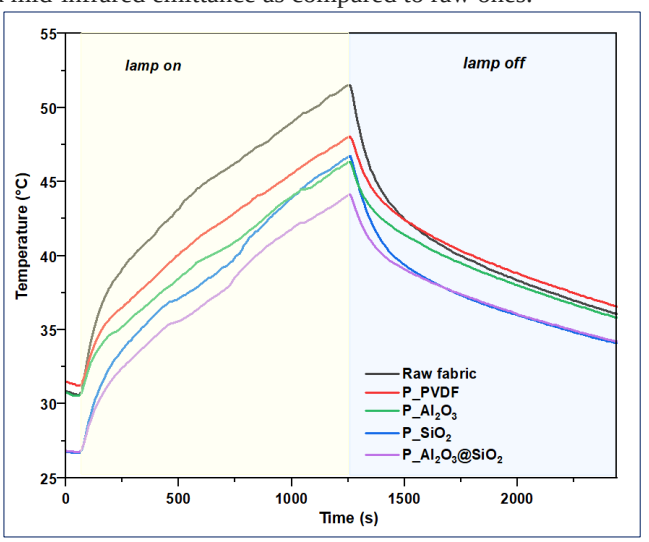

Figure 5: Real-time temperature curves of the raw fabric, P_PVDF, P_Al_2O_3, P_SiO_2, P_Al_2O_3@SiO_2 samples

Flame retardant performance of the raw and treated fabric was determined in accordance with standard AATCC 6941 and corresponding results presented in Figure 6. As seen in Figure 6, the raw fabrics displayed a 4 cm char length with visible structural degradation upon flame exposure. The P_Al_2O_3 one showed the highest char length with 12 cm among the all samples accompanied by extensive fabric damage and significant char formation, suggesting that the Al_2O_3 coating tends to decompose rather than play a flame-retardant role in the system, thus showing a flammable phenomenon under the applied test conditions. The P.SiO_2 sample demonstrated a moderately improved flame resistance with a char length of 10.5 cm; however, considerable burning damage was still observed on the fabric surface. Upon the incorporation of the binary Al_2O_3@SiO_2 particles, the flame retardancy improved progressively, achieving the lowest char length of 1.8 cm with minimal fabric degradation. This may be resulted from Al_2O_3@SiO_2 binary structure rapidly form a cohesive inorganic protective barrier on the fabric surface, which effectively retards heat transfer to the underlying substrate and inhibits further flame propagation.

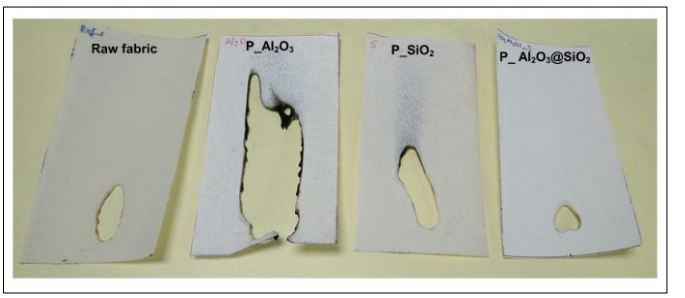

Figure 6: Photographs of the raw fabric, P_PVDF, P_Al_2O_3, P_SiO_2, P_Al_2O_3@SiO_2 samples following flame test

Additionally, self-cleaning function is also necessary for practical applications to prevent dirt and various droplets from compromising the performance of the passive radiative cooling curtain. As shown in Figure 7 (a), when various solutions (methylene blue dye, water, and coffee) were dropped onto the P_Al_2O_3@SiO_2 samples which have highest cooling performance the droplets maintained a quasi-spherical geometry, demonstrating the coating's excellent antipollution properties. Also, a controlled amount soil was deposited on to the sample surface followed by rinsing with water droplets from a rubber dropper to determine self-cleaning capability. As seen in Figure 7 (b), the contaminants were removed from the surface of P_Al_2O_3@SiO_2 sample. These results verify that the micro-nano porous composite structure within the film provides self-cleaning ability, helping to preserve the material's optical and thermal performance in practical application.

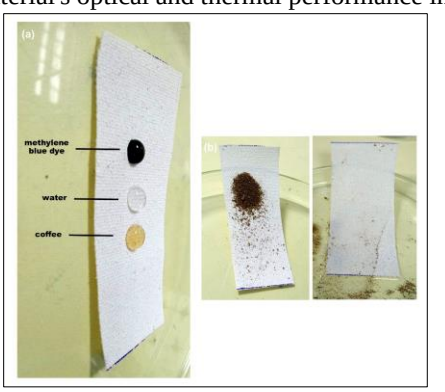

Figure 7: Droplets of different contaminants on the surface (a), self-cleaning capability of P_Al_2O_3@SiO_2 (b)

4. CONCLUSION

In this study, multifunctional passive radiative cooling curtain fabrics were successfully developed with porous PVDF nanocomposite coatings including SiO_2, Al_2O_3, and binary Al_2O_3@SiO_2 nanoparticles by solvent exchange phase separation and spray coating process. Nanocomposite treated especially including binary Al_2O_3@SiO_2 particles exhibited the most effective passive cooling performance with 7.38°C temperature drop

under 500 W/m^2 solar irradiance based on higher solar reflectance (77.64%) and mid-infrared emittance (88.16%) due to the synergistic effect of the binary nanoparticle structure and hierarchical porous coating morphology. In addition to radiative cooling performance, binary Al_2O_3@SiO_2 particle also remarkably enhanced flame retardancy, yielding the lowest char length (1.8 cm) with minimal structural degradation after flame exposure. Also, this sample endows sufficient self-cleaning performance, which is essential for maintaining long-term optical and cooling performance in practical applications. Summing up, this developed curtain fabric presents a promising approach for sustainable building thermal management by simultaneously combining passive cooling, flame retardancy, and self-cleaning functionalities.

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DIGITAL SASHIKO: A COMPUTATIONAL FRAMEWORK FOR AUTOMATED TEXTILE REPAIR VIA ADDITIVE MANUFACTURING

Professional paper
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ABSTRACT: *Extending the functional lifetime of garments is a critical pillar of textile circularity, yet manual repair remains a significant bottleneck due to the high level of skill and time required. The present research introduces "Digital Sashiko" a workflow that integrates computational design with additive manufacturing to automate the structural reinforcement of damaged textiles. Inspired by the Japanese tradition of visible mending, the proposed method utilizes Grasshopper™ to generate algorithmic patterns that are topographically mapped to specific garment tears.*
The study investigates the use of Thermoplastic Polyurethane (TPU) for its high elasticity and superior interfacial bonding, ensuring that the mended area retains the necessary flexibility for wearable applications. By treating the textile as a primary substrate for direct-to-garment printing, this research explores the mechanical interlocking between the polymer and fabric weave to enhance garment longevity. This computational approach transforms the "visible mending" philosophy into a precise, scalable industrial process, addressing key barriers to clothing repair and advancing the goals of a circular fashion economy.

Keywords: *3D Printing, Sashiko, Grasshopper, TPU, Circular Design, Textile Adhesion, Visible Mending.*

DIGITALNI SAŠIKO: RAČUNARSKI OKVIR ZA AUTOMATIZOVANU POPRAVKU TEKSTILA PUTEM ADITIVNE PROIZVODNJE

APSTRAKT: *Produžavanje funkcionalnog veka trajanja odeće predstavlja kritičan stub cirkularnosti tekstila, ali ručni popravci i dalje predstavljaju značajnu prepreku zbog visokog nivoa veštine i vremena koje su potrebni. Ovo istraživanje predstavlja „Digitalni*

Sašiko“, tok rada koji integriše računarski dizajn sa aditivnom proizvodnjom kako bi se automatizovalo strukturno ojačanje oštećenih tekstila. Inspirisan japanskom tradicijom vidljivog popravljanja, predložena metoda koristi Grasshopper™ za generisanje algoritamskih uzoraka koji su topografski mapirani na specifična oštećenja na odeći.
Studija ispituje upotrebu termoplastičnog poliuretana (TPU) zbog njegove visoke elastičnosti i superiornog međupovršinskog vezivanja, čime se obezbeđuje da popravljeno područje zadrži neophodnu fleksibilnost za nošenje. Tretirajući tekstil kao primarnu podlogu za direktno štampanje na odeći, ovo istraživanje istražuje mehaničko preplitanje između polimera i tkanine kako bi se poboljšao vek trajanja odeće. Ovaj računarski pristup pretvara filozofiju "vidljivog zakrpljivanja" u precizan, skalabilan industrijski proces, rešavajući ključne prepreke u popravci odeće i unapređujući ciljeve cirkularne modne ekonomije.

Ključne reči: *3D štampanje, Sašiko, Grasshopper, TPU, cirkularni dizajn, adhezija tekstila, vidljivo zakrpljivanje.*

1. INTRODUCTION

The fashion and textile industry is one of the largest contributors to global waste and carbon emissions, with fast fashion creating a culture of disposability, where garments are discarded instead of repaired, significantly shortening their lifespans. While extending garment lifespans is a critical circular strategy, practical pathways for scalable repair remain underexplored [1, 2].
Traditional textile repair methods, such as darning, patching and hand-stitching, require a high degree of manual skill and are time-consuming. While cultural practices like the Japanese Sashiko, a form of functional embroidery that reinforces worn fabric with running stitches, demonstrate the aesthetic and structural potential of visible mending, they cannot be realistically adapted to industrial-scale production. This gap between artisanal repair and scalable manufacturing represents a significant opportunity for computational and digital fabrication technologies [1, 3].
Additive manufacturing (AM) has demonstrated considerable versatility in depositing materials onto complex substrates. Recent advances in direct-to-textile 3D printing have shown that thermoplastic elastomers can be bonded directly to fabric surfaces, creating flexible, durable composite structures. Fused Deposition Modelling (FDM) with Thermoplastic Polyurethane (TPU) filament is particularly promising due to the material's elasticity and adhesive properties on textile substrates [4, 5].
Furthermore, parametric and algorithmic design tools such as Grasshopper™, a visual programming environment for Rhinoceros 3D, facilitate the generation of complex, geometry-driven patterns that can be adapted to specific repair scenarios. The combination of these tools creates a new paradigm: the automated, computationally driven structural repair of textiles.
This paper presents "Digital Sashiko", a comprehensive workflow that integrates Grasshopper™-based algorithmic pattern generation with fused filament fabrication (FFF)

3D printing using TPU to perform structural reinforcement on a cotton-polyester blend textile substrate. The goal is to translate the aesthetic and functional philosophy of Sashiko into a precise, repeatable, and scalable industrial process that addresses the core barriers of clothing repair within a circular economy context.

2. BACKGROUND AND RELATED WORK

2.1. The Sashiko Tradition and Visible Mending

Sashiko is a Japanese stitching technique historically used to reinforce and repair textiles, particularly work garments and quilted layers of fabric worn for warmth. The term translates roughly as “little stabs”, and the technique produces geometric patterns of running stitches, typically in white thread on indigo-dyed fabric. Beyond its functional role in reinforcing worn fabric, it is distinguished by its deliberate visibility, the mend is not hidden but celebrated as evidence of care and continued use [3, 6].

The contemporary “visible mending” movement draws on this philosophy, reframing repair as a creative and ethical practice in opposition to disposable consumption. While this movement has gained cultural traction, its dependence on manual skill limits its scalability and potential for industrial application.

2.2. Additive Manufacturing on Textiles

The use of 3D printing directly on fabric substrates has been an active area of research. Studies have demonstrated that FFF printing with flexible filaments such as TPU can achieve strong mechanical bonds with woven and knitted textiles through a combination of thermal bonding and mechanical interlocking between the deposited polymer and the fabric weave structure [4]. Key parameters affecting bond strength include print temperature, bed temperature, layer height, and fabric weave density [4, 5, 7].

TPU is particularly favoured for textile applications due to its high elongation at break, excellent abrasion resistance, and the fact that its flexible nature does not restrict the natural drape and movement of the fabric. Research has shown that the first printed layer is critical for adhesion, as it must penetrate the textile surface sufficiently to create a mechanical interlock without causing thermal damage to the fibres [4, 5].

2.3. Algorithmic and Computational Pattern Design

Grasshopper^{TM} is a visual dataflow programming interface for the Rhinoceros3D^{TM} computer-aided design (CAD) environment. It enables the parametric and algorithmic generation of geometry, allowing designers to automate the production of complex forms via the definition of rule-based systems. Its application in textile design has been explored for generating knit structures, weave patterns, and surface textures, including for direct-to-textile printing workflows [8, 9, 10, 11], but its use in the context of structural textile repair is novel.

By encoding the geometric logic of traditional Sashiko patterns into algorithmic rules, Grasshopper^{TM} can generate repair geometries that are topographically mapped and conformed to the specific shape and extent of a garment tear. This approach moves beyond

fixed templates, allowing the repair pattern to adapt dynamically to different damage profiles.

3. METHODOLOGY

3.1. Overview of the Digital Sashiko Workflow

The Digital Sashiko workflow consists of four primary phases: (1) damage assessment and digitisation, (2) computational pattern generation in Grasshopper^{TM}, (3) toolpath preparation and FFF printing with TPU, and (4) geometric and aesthetic evaluation.

3.2. Damage Assessment and Digitisation

The extent and geometry of a fabric tear were documented through image-based digitisation. Damaged garment panels were photographed and the resulting bitmap image was imported directly into the Grasshopper^{TM} definition using the Vectorize^{TM} plugin. The boundary was extracted computationally using said plugin within Grasshopper^{TM}, applying a binary threshold of 0.5 and a 100-pixel speckle filter to eliminate texture noise (Figure 1).

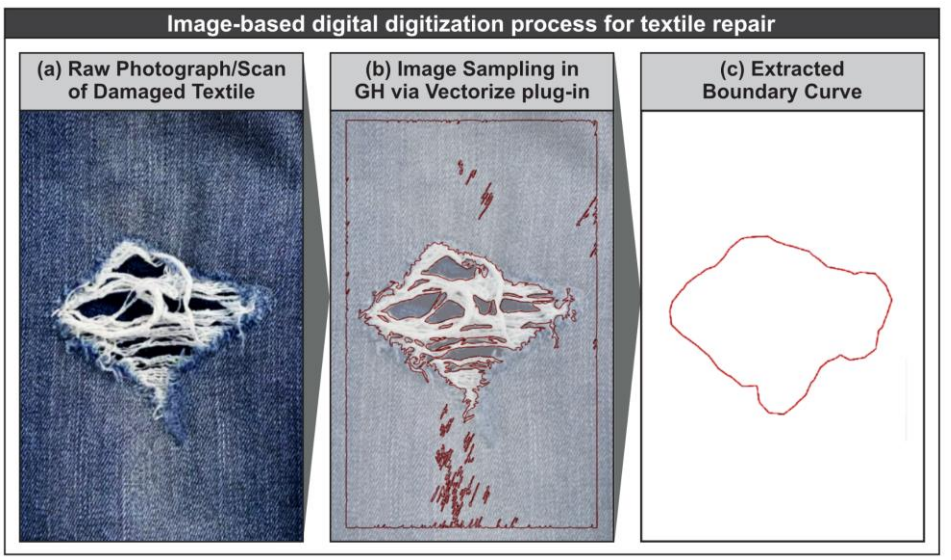

Figure 1: Digitised garment tear with extracted boundary curve

The resulting contour curves were further cleaned and remapped to produce a single closed boundary curve, which served as the target geometry for the pattern-generation stage described in Section 3.3.

3.3. Algorithmic Pattern Generation in Grasshopper™

A parametric Grasshopper™ definition was developed to generate Sashiko-inspired repair patterns and conform them to the geometry of the identified tear. The definition operates in three stages (Figure 2).

First, a base stitch-pattern grid is generated parametrically. A Stream Filter component allows the designer to switch between several candidate grid topologies, including rectangular, radial, hexagonal, and triangular arrangements, each driven by two shared parameters: a base cell Size and a pattern Extent that controls the overall density and repeat count of the grid. For the case presented here, the radial topology was selected, producing a fan of concentric and radiating cells reminiscent of traditional Sashiko motifs. The selected grid is converted into a mesh, which forms the topological “skeleton” of the repair pattern and provides the set of vertices and edges manipulated in the following stage.

Second, the base grid and its derived mesh are topographically mapped onto the tear boundary curve obtained in Section 3.2 through a physics-based relaxation step using the Kangaroo2™ solver. The base grid establishes the initial fit, while the mesh is conformed to the tear boundary through combined Length, On-Curve, and Direction goals to maintain pattern character despite the irregular tear shape. To optimize computational responsiveness, the solver is triggered manually, converging within seconds.

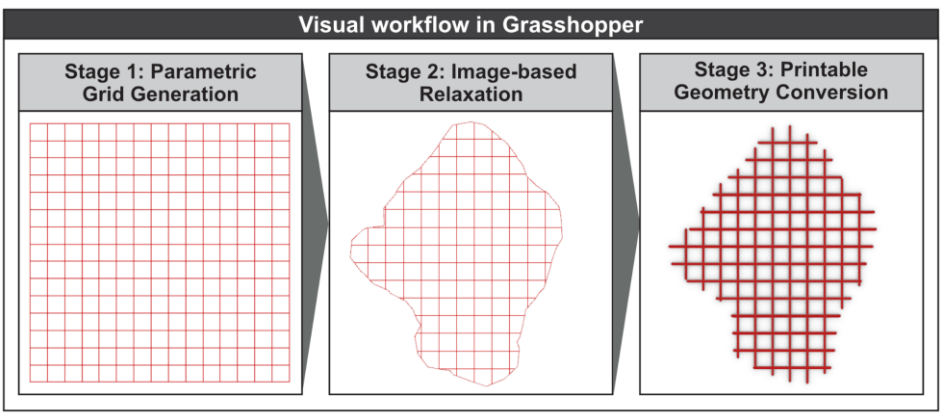

Figure 2: Grasshopper™ definition showing (left) parametric grid-type selection and base mesh generation, (centre) image-based tear curve extraction and Kangaroo2™ relaxation goals (Length, On-Curve, Direction), and (right) the solved mesh converted to printable pipe geometry

Third, once the mesh has relaxed onto the tear boundary, its edges are converted into solid, printable geometry using a pipe operation, in which a uniform radius (set to 0.7 mm in this study) is applied along each edge to generate a tubular mesh representing the raised TPU stitch lines. This final mesh is exported directly for slicing and 3D printing.

3.4. Material and Print Parameters

FFF printing was performed using a Bambu^{TM} Lab P2S 3D printer (Bambu Lab Co., Ltd., Shenzhen, China). The key print parameters were set as follows and refined through a series of preliminary adhesion tests:

Table 1: FFF print parameters for TPU direct-to-textile printing

1 Parameter	2 Value
Material	TPU 95A
Nozzle temperature	230 °C
Bed temperature	35 °C
Layer height	0.20 mm
First layer height	0.20 mm
Nozzle diameter	0.40 mm
Chamber temperature	30 °C
Elephant foot compensation	0.15 mm
Print speed	30 mm/s
Infill density / pattern	15% / Gyroid

3.5. Printing Process

The fabric substrate was secured flat on the print bed using heat-resistant adhesive tape. The pipe-converted mesh produced by the Grasshopper^{TM} definition (Section 3.3) was exported as an STL file and sliced using Bambu^{TM} Studio (v1.10, Bambu Lab Co., Ltd.). The print paths were designed to deposit TPU filament along the stitch-pattern lines, creating a raised polymer structure on the fabric surface that replicates the visual appearance of Sashiko stitching while simultaneously reinforcing the tear boundary through mechanical interlocking with the weave (Figure 3).

4. RESULTS AND DISCUSSION

4.1. Geometric Fidelity and Pattern Versatility

The continuity and structural distribution of the printed TPU patterns were evaluated across the tested cotton-polyester blend fabric substrate, demonstrating high geometric fidelity. As shown in Figure 4, the computational framework successfully translates different algorithmic grid topologies, including rectangular, triangular, and radial configurations, into physical, well-defined polymer structures directly bonded to the textile surface.

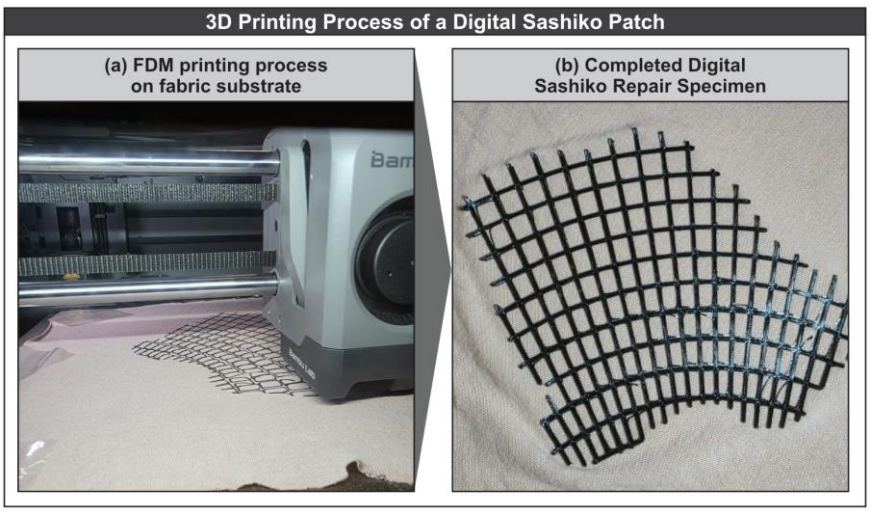

Figure 3: (a) FFF printing process on fabric substrate; (b) completed Digital Sashiko repair specimen

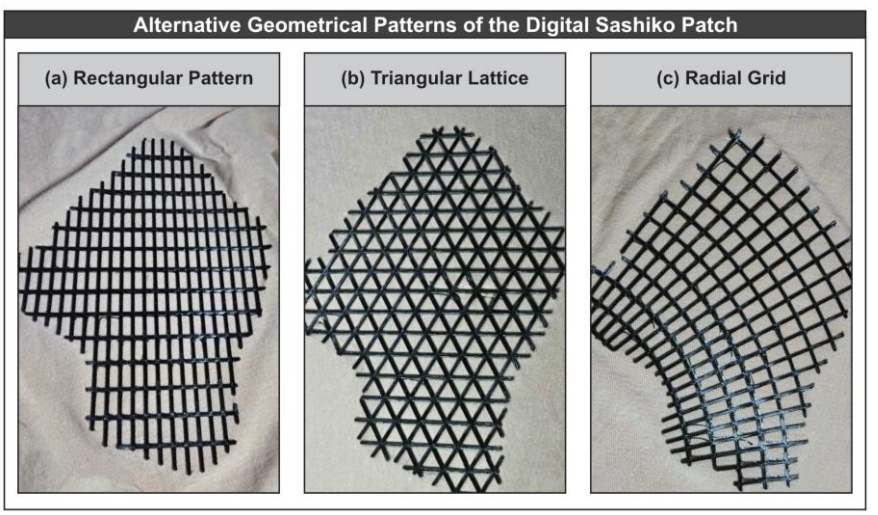

Figure 4: Macro-views of printed specimens showcasing pattern versatility: (a) Rectangular Pattern, (b) Triangular Lattice, and (c) Radial Grid

This multi-pattern capability confirms that the Grasshopper^{TM} definition can dynamically adapt the visual and structural density of the mend based on the specific aesthetic or directional flexibility required by the garment.

4.2. Aesthetic Integration and the Visible Mending Principle

The Digital Sashiko approach produces a repair that is visually prominent by design. The raised TPU stitch lines are clearly visible on the fabric surface, translating the cultural philosophy of Sashiko into the language of digital fabrication. An informal visual evaluation conducted with five participants confirmed that the geometric patterning was perceived as intentional and decorative rather than as a defect, with all participants identifying the repair as a design feature. The parametric nature of the Grasshopper^{TM} definition allows the pattern geometry, stitch density, and orientation to be customized per garment (Figure 5).

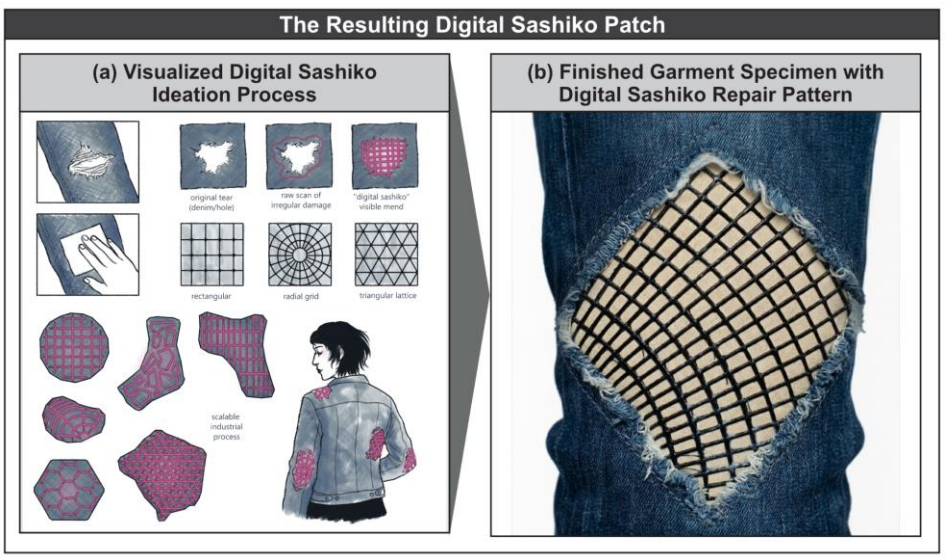

Figure 5: Finished garment specimen with Digital Sashiko repair pattern

4.3. Scalability and Industrial Applicability

The workflow presented in this study is designed with scalability in mind. The Grasshopper^{TM} definition is non-destructive and fully parametric, meaning it can be adapted to any tear geometry without manual redesign. Integration with automated damage detection systems, such as computer vision or structured light scanning, could enable a largely automated pipeline from damage identification to repair fabrication. This has

significant implications for garment repair services, rental fashion platforms, and textile recycling operations seeking to extend product lifecycles efficiently.

5. CONCLUSION

This paper has presented Digital Sashiko, a computational framework for the automated structural repair of damaged textiles using Grasshopper^{TM}-driven algorithmic pattern generation and FFF 3D printing with TPU. The proposed workflow bridges the cultural and philosophical tradition of Japanese visible mending with the precision and scalability of digital fabrication.

Building on established principles of TPU-textile bonding, qualitative manual handling of the physical prototypes confirmed that the printed open-grid structures easily maintain fabric flexibility without experiencing cracking or delamination. The Grasshopper^{TM}-based pattern generation demonstrated high geometric fidelity, enabling the dynamic adaptation of varied grid topologies and repair geometries to specific damage profiles. This transforms an artisanal repair practice into a repeatable, parameter-driven industrial process.

The Digital Sashiko approach directly addresses key barriers to scalable garment repair, skill requirements, time costs, and aesthetic stigma, and thus represents a meaningful contribution to the goals of circular fashion. Future work could focus on integrating automated damage detection via computer vision, exploring multi-material printing for enhanced aesthetic and functional differentiation, and conducting user studies to evaluate consumer acceptance of visibly repaired garments produced through this method.

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INVESTIGATION OF MICROWAVE-ASSISTED NATURAL DYEING USING HOUSEHOLD FOOD WASTE

Scientific paper
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ABSTRACT: *Nowadays, waste management goes beyond being merely an environmental necessity and plays a vital role in achieving sustainable development goals. This has increased the demand for more sustainable production methods, particularly in the textile industry, where water, energy and chemicals are used intensively. In this context, microwave-assisted dyeing has recently emerged as a popular method in sustainable natural dyeing applications due to its eco-friendly, sustainable and cost-effective nature. In this study, onion peel, a domestic food waste product, was used as a dye for 100% cotton woven fabrics. To enhance the efficiency of the dyeing process, alum ($KAl(SO_4)_2 \cdot 12H_2O$), a traditional mordant, was used, whilst pomegranate peel, spurge (Euphorbia) and pine cones were employed as bio-mordants. The effect of microwave-assisted dyeing, applied at different durations, on colour properties was investigated in comparison to traditional dyeing. The CIELAB colour parameter values and colour strength (K/S) values of the dyed fabrics were calculated. Principal Component Analysis (PCA) was used to examine the relationship between the parameters in greater detail. It is considered that onion peel can be effectively utilised in sustainable dyeing, particularly in microwave-assisted dyeing processes, and that the biomordants used can make a positive contribution to the dyeing process as environmentally friendly and alternative auxiliary agents. It is anticipated that the findings will contribute to the development of alternative and environmentally friendly processes in the field of natural dyeing.*

Keywords: *Sustainability, natural dyeing, PCA, microwave, biomordant.*

MIKROTALASIMA POTPOMOGNUTO BOJENJE KORIŠĆENJEM OTPADA OD HRANE

APSTRAKT*: U današnje vreme upravljanje otpadom prevazilazi samo ekološku potrebu i igra vitalnu ulogu u postizanju ciljeva održivog razvoja. Ovo je povećalo potražnju za održivijim metodama proizvodnje, posebno u tekstilnoj industriji, gde se voda, energija i*

hemikalije intenzivno koriste. U tom kontekstu, bojenje uz pomoć mikrotalasa se nedavno pojavilo kao popularna metoda u održivim procesima bojenja zbog svoje ekološke, održive i isplative prirode. U ovoj studiji, ljuska crnog luka, proizvod od otpada hrane iz domaćinstva, korišćena je kao boja za 100% pamučne tkanine. Da bi se poboljšala efikasnost procesa bojenja, korišćena je stipsa ($KAl(SO_4)_2 \cdot 12H_2O$), tradicionalno sredstvo za močenje, dok su kora nara, mlječika (Euphorbia) i šišarke korišćeni kao biomočila. Ispitan je efekat bojenja uz pomoć mikrotalasa, primenjenog u različitim trajanjima, na svojstva boje u poređenju sa tradicionalnim bojenjem. Izračunate su vrednosti parametara boje CIELAB i vrednosti jačine boje (K/S) obojenih tkanina. Analiza glavnih komponenti (PCA) korišćena je za detaljnije ispitivanje odnosa između parametara. Smatra se da se ljuska crnog luka može efikasno koristiti u održivom bojenju, posebno u procesima bojenja uz pomoć mikrotalasa, i da korišćena biomočila mogu pozitivno doprineti procesu bojenja kao ekološki prihvatljiva i alternativna pomoćna sredstva. Očekuje se da će nalazi doprineti razvoju alternativnih i ekološki prihvatljivih procesa u oblasti prirodnog bojenja.

Ključne reči: *Održivost, prirodno bojenje, PCA, mikrotalasi, biomočila.*

1. INTRODUCTION

Sustainability in the textile industry involves preserving ecological balance, preventing the depletion of natural resources, and ensuring that production does not endanger human lives. Traditional textile dyeing processes pose a serious threat to the environment and human health due to high water and energy consumption, carcinogenic and toxic effects, and the presence of heavy metals. Consequently, the adoption of eco-friendly dyeing practices has accelerated globally [1]. The integration of natural dyes, biomaterials, and advanced technologies in the textile industry aligns directly and strongly with the United Nations Sustainable Development Goals (SDGs) [2].

For natural dyeing, the roots, stems, and leaves of plants, as well as fungi, algae, insects, and various minerals, can be used. In natural dyeing, biomordants – which are entirely biological and environmentally friendly – can serve as alternatives to traditional metal mordants, which help dyes adhere more strongly to fabrics [3]. These natural dyes and biomordants can impart low toxicity, biodegradability, antimicrobial activity, antioxidant properties, and UV-protective effects to the dyed fabrics [1,4–5].

In sustainable natural dyeing processes, the microwave dyeing method can also be used as an alternative to conventional dyeing methods. Microwave dyeing enables processes to be completed in a shorter time by providing high energy efficiency. Due to rapid penetration, high yields can be achieved at lower temperatures and with reduced water usage. In these respects, it supports a sustainable production approach and is fully aligned with the Sustainable Development Goals (SDGs) [6–8].

In this study, 100% cotton fabrics were mordanted using the microwave method with various biomordants and a metal mordant. The mordanted fabrics were dyed using onion peel derived from domestic waste as a dye source, both under microwave energy for varying durations and via the conventional method. The colour properties of the samples

were evaluated using CIELAB parameters and L/B values, and the results were statistically analysed using Principal Component Analysis (PCA).

2. MATERIALS AND METHOD

A 100% cotton plain-weave fabric was used for this study.

2.1 Mordanting process

A pre-mordanting process was used in the study. Pomegranate peel, spurge (Euphorbia), pine cone bio-mordant, and the metal mordant aluminium potassium sulphate (KAl(SO4)2.12H2O) were used for mordanting. The mordanting process was conducted for 5 minutes using 700 W of microwave energy. The concentration of the mordants was set at 5% by weight of the fabric.

2.2 Dyeing process

Dye concentrations were calculated based on fabric weight; a 50% concentration (o.w.f.) of onion peel waste derived from domestic sources was utilized. The microwave dyeing process was conducted using 700 W microwave energy for 5, 7, and 15 minutes. Additionally, a conventional dyeing process was applied to the fabrics for 15 minutes at boiling temperature.

2.3 Colour measurement

Following the pre-mordanting and dyeing processes, the colour values were measured using an LS175 colourimeter. Measurements were taken under a D65 light source and 10° standard observer conditions. Reflectance (R) values were obtained in the visible range (400–700 nm) and converted to colour strength (K/S) values using the Kubelka–Munk equation (Equation 1).

$$K/S = (1 - R)^2 / 2R \quad (1)$$

2.4 Principle component analysis

Principal Component Analysis (PCA) was used to evaluate the relationships between the dyeing parameters and the colour characteristics of the fabrics after dyeing. PCA was performed using OriginLab 2024 software to visualise the distribution of the dyed fabrics and the correlations between the variables.

3. RESULTS AND DISCUSSION

Table 1 shows the effects of various mordant types and dyeing methods on the colour properties of fabrics.

Table 1: Colour data for dyed and mordanted fabrics

Samples	L*	a*	b*	C*	h°	λ	K/S
STD	90.46	-0.75	1.60	1.75	115.2	400	0,25
E	88.47	-0.19	5.05	5.05	92.2	400	0,30
A	90.66	-1.10	2.78	2.98	111.5	400	0,29
P	86.03	0.58	7.49	7.51	85.5	400	0,39
5MW	86.08	1.34	10.93	11.01	83.0	400	0,61
7MW	82.44	4.16	17.40	17.89	76.5	400	1,71
15MW	75.33	9.71	21.46	23.55	65.6	400	2,55
15C	81.32	5.04	18.22	18.90	74.5	400	1,65
P5MW	81.57	3.13	17.58	17.84	79.8	400	1,49
P7MW	81.53	3.79	16.02	16.45	76.6	400	1,43
P15MW	78.35	6.67	18.17	19.35	69.8	400	1,85
P15C	80.02	4.28	20.02	20.46	77.9	400	1,89
E5MW	83.51	2.74	15.05	15.28	79.6	400	1,14
E7MW	83.17	2.38	14.99	15.17	80.9	400	1,20
E15MW	75.58	9.61	21.85	23.86	66.1	400	2,82
E15C	77.08	7.93	19.24	20.81	67.6	400	2,18
A5MW	76.30	4.59	45.67	45.90	84.2	400	4,12
A7MW	70.50	9.31	54.94	55.72	80.3	400	8,00
A15MW	67.59	10.86	54.99	56.05	78.8	400	9,64
A15C	72.60	7.30	50.98	51.50	81.8	400	6,09
PC5MW	83.32	2.86	15.27	15.53	79.3	400	1,21
PC7MW	83.19	2.55	15.61	15.81	80.6	400	1,14
PC15MW	74.81	9.65	21.12	23.22	65.4	400	2,71
PC15C	79.54	5.29	18.56	19.29	74.0	400	1,90

L * Lightness (0 = black, 100 = white), ; **a*** ± Red/green, ; **b*** ± Yellow/blue, **C *** To vividness-dullness (100 = vivid, 0 = dull),
A: aluminium potassium sulphate (KAl(SO4)2.12H2O) mordant P: Pomegnate peel biomordant E: *Euphorbia* biomordant PC: Pine cone biomordant MW: Microwave dyeing C: Conventional dyeing

A decrease in L* values was observed after application, except for the aluminium-mordanted and unpainted sample. The lowest brightness value was recorded in the A15MW sample. There is an inverse relationship between application time and brightness values. Microwave dyeing caused a greater reduction in brightness than conventional dyeing over the same period. Among the mordant types, the lowest brightness was found in samples mordanted with aluminium potassium sulphate (A).

The a* values of the samples shifted towards the red region after the dyeing process. The sample with the reddest hue is coded A15MW. Samples dyed using a microwave for the same duration show higher a* values. The highest a* values are found in the samples

coded A. The b* value, which represents the yellow and blue hue, increased in the yellow region after the mordanting and dyeing process. As with the a* value, the highest b* values are found in the samples coded A, with the highest value in the sample coded A15MW. The positive effect of microwave application is also evident in this value. Regarding C* chroma values, the saturation of the samples increased after the mordanting and dyeing process. While samples mordanted with natural mordant yielded similar results, those mordanted with aluminium potassium sulphate ($KAl(SO_4)_2 \cdot 12H_2O$) (A) exhibited higher values than the other samples. When the samples are examined in terms of hue values (h°), it is evident that, except for those coded STD, E, and AL (in the yellow region), the samples fall within the orange-yellow region. The K/S value is known as colour strength. In terms of colour strength values, the dyed samples have higher values than the undyed samples, and it is generally observed that colour strength values increase with longer microwave application times. Additionally, as with other values, the best colour strength values are observed in the samples coded A, with the highest value in the A15MW sample.

In samples treated with natural mordant, the highest values are found in those labelled ‘E’. The CIE L*-b* chromaticity diagram clearly shows the differences in L* and b* values among samples without mordant, those treated with natural mordant, and those treated with aluminium mordant (Figure 1).

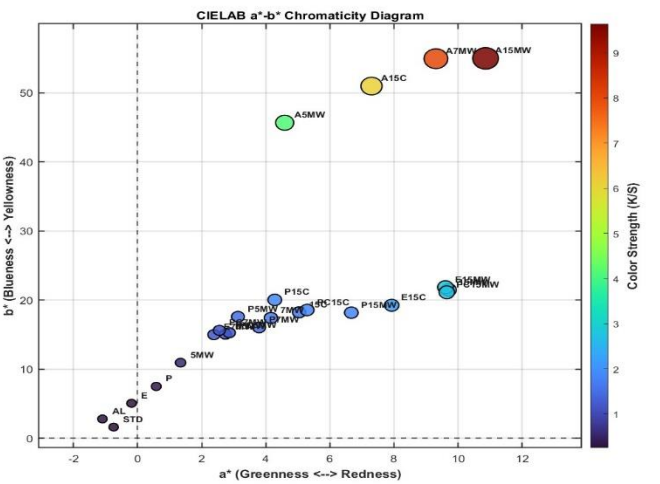

Figure 1: Cıelab a*-b* Chromaticity Diagram

The Lightness vs. Chroma Distribution graph clearly demonstrates the inverse relationship between lightness and chroma, while the clustering of the A-coded samples indicates that they have the highest chroma and lowest lightness values (Figure 2).

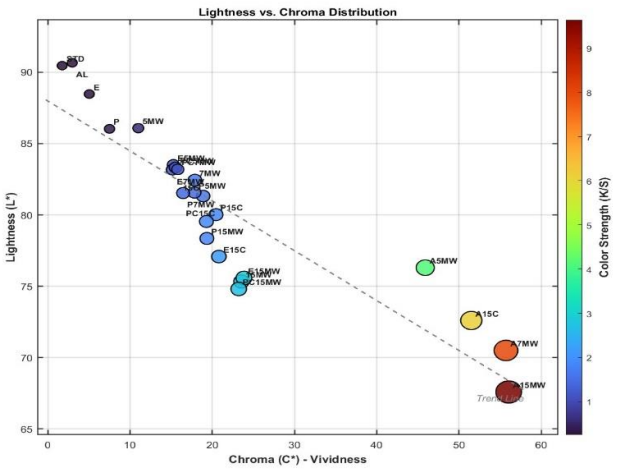

Figure 2: Lightness vs. Chroma Distribution

The visual representation of the Trend of Colour Strength across Heating Methods and Mordants also demonstrates the superiority of aluminium mordant and microwave application (Figure 3).

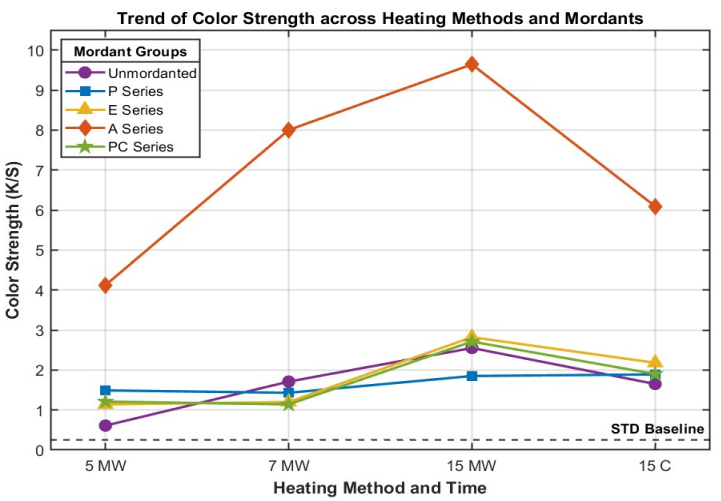

Figure 3: Trend of colour Strength across Heating Methods and Mordants

The eigenvalue plot shows that the values of PC1 and PC2 are greater than 1, indicating that the relationships between these two dimensions and the parameters can be explained (Figure 4). The PC1 and PC2 plot shows that PC1 (63.83%) and PC2 (18.49%) together

account for 82.32% of the total variation (Figure 5). This indicates that these axes explain 82.32% of the total variation. A strong positive correlation is observed between the MT, C*, b*, and K/S values in the PC1 and PC2 plot. There is a negative correlation between the L* value and these variables, indicating that as vibrancy and colour strength increase, brightness decreases. There is a positive correlation between the DT, DTI, and a* values, and a negative correlation between these values and the h and L values.

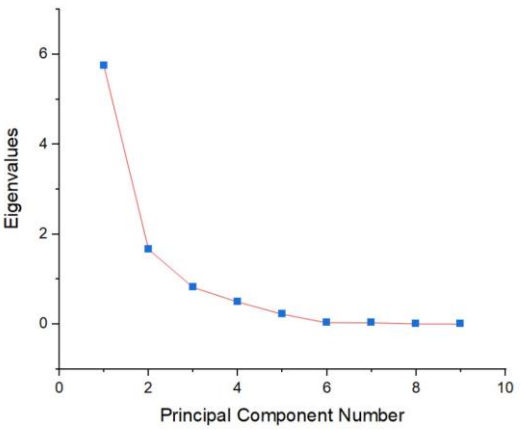

Figure 4: Eigenvalue graphs

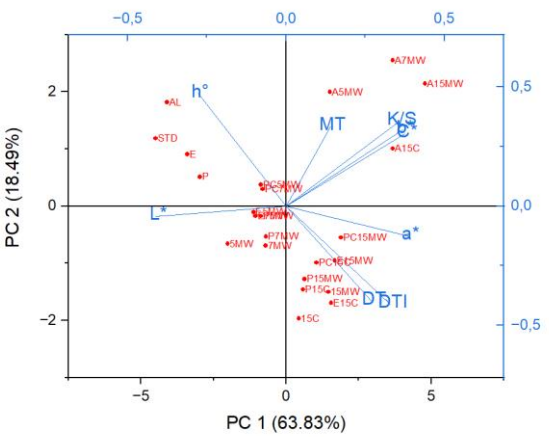

Figure 5: PC1 and PC2 plot

4. CONCLUSION

This study has shown that the microwave method produces faster and more effective results than the traditional method when dyeing 100% cotton fabrics with onion peel waste. The analyses revealed that fabrics dyed with aluminium potassium sulphate (A) achieved the highest colour strength (K/S) and saturation values, resulting in the deepest and most vivid colour tones, especially with a 15-minute microwave application (A15MW). It was observed that as the microwave duration increased, brightness (L*) decreased while colour saturation increased. Statistical data (PCA) confirmed the strong correlation between these parameters. In conclusion, the combination of aluminium mordant and microwave energy can be considered a sustainable, efficient and high-performance alternative method for using natural waste in textile dyeing.

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LAST INOVATIONS IN ZIPPER MARKET

Review paper
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ABSTRACT: *For nearly a century a construction and materials of the zippers are constantly improved, however significant innovative changes has been offered only during the last decade. Increased functionality zippers are developed to support water and airproof properties of final textile goods, to ease their closing and opening process and to extend the life cycle of zippers making them repairable by their users. Sustainable zippers are made from recycled or bio-based polyester and nylon while their tapes can be woven from organic cotton, linen or hump. Finishing process of metal teeth is done using low-emission coatings. The raw materials, production methods or disposal ways of eco-friendly zippers support environmental protection aims. The leading zipper company YKK has developed the most revolutionary solutions, such us, toothless zippers, tapeless zippers, touch-link and self-propelled zippers.*

Keywords*: zippers, waterproof, recycling, bio-based materials, organic materials.*

POSLEDNJE INOVACIJE NA TRŽIŠTU PATENTNIH ZATVARAĆA

APSTRAKT: *Tokom gotovo jednog veka konstrukcija i materijali za izradu patentnih zatvarača kontinuirano su unapređivani, dok su značajne inovativne promene razvijene tek tokom poslednje decenije. Savremeni patentni zatvarači unapređene funkcionalnosti doprinose poboljšanju vodoodbojnih i vazduhonepropusnih svojstava finalnih tekstilnih proizvoda, olakšavaju proces otvarnja i zatvaranja, kao i produženju njihovog životnog ciklusa. Održivi patentni zatvarači izrađuju se od reckliranih i biobaziranih poliesterskih i najlonskih materijala, dok se njihove trake tkaju od organskog pamuka, lana ili konoplje. Dorada metalnih zubaca se izvodi sa ekološki prihvatljivim metodama niske emisije. Vodeća kompanija u proizvodnji patentnih zatvarača YKK razvila je najrevolucionarnije inovacije u ovoj oblasti, uključujući patentne zatvarače bez zubaca, bez trake, čipovane i motorizovane patentne zatvarače.*

Ključne reči: *patentni zatvarać, vodoodbojnost, recikliranje, biobazirani materijali, organski materijali.*

1. INTRODUCTION

The first metal teeth zippers were invented in 1913 by Swedish engineer Gideon Sundback. After World War II when polymer technology and die-casting process for plastics improved, moulded plastic teeth zippers were created [1]. Being lighter, corrosion resistant and easy manufactured in wide variety of colours, they replaced metal zippers in many applications. In late 1840s fastener companies introduced the third kind of zippers - nylon coild zippers. The construction of their teeth allowed to create very light fasteners used with light fabrics and invisible /reverse side fasteners for applications where fastener has to be unnoticeable [1,2].
For nearly a century a construction and materials of the zippers are constantly improved, however significant changes for such kind of fastening system has been offered only during the last decade. Today's manufacturers are developing zippers with increased functionality, sustainable zippers, water and air impenetrable zippers [1]. The most revolutionary ideas are offered by leading Japanese company YKK designing their tapeless, toothless, and self-propelled zippers. The well-known manufacturers of zippers in the market are: SBS (China), KCC (China), Riri Group (Switzerland), Talon International (USA), LenZip (USA), ZlideOn (Sweden), Olympic zippers (India), others.

2. ZIPPERS WITH INCREASED FUNCTIONALTY

Increased functionality zippers are developed to widen the application of such kind of fasteners, (for example, to use them in conditions where closure have to be water or even air proof), to ease closing or opening of garments and to extend the life cycle of zippers making them repairable by their users.

2.1. Waterproof zippers

To block water penetration the tape, gare system and a slider section of waterproof zippers are manufactured from special materials using new and advanced technologies [2, 3].The tape of a zipper is created from waterproof plastic, rubber or tightly woven polyester, nylon, or vinyl base which is covered with hydrophobic polymer - polyurethane (PU) or thermoplastic Polyurethane (TPU) film. TPU coating is suitable for heavy duty waterproof zippers as it ensures high strength, water, moisture and corrosion resistance (see Fig.1).
The molded teeth are made from flexible plastic or rubber covered with PU film. They use to be squeezed by a slider closing the zipper. After the slider passes, the teeth relax and with it close any gap in between them. The teeth of waterproof coil zippers are placed on the reverse side to expose the tape not the teeth to the moisture and water (see Fig.1). [4,5]. If a zipper has metal teeth they are coated with TPU film.

Figure 1: Waterproof reverse side coil zipper by a company OSO

There are available also toothless waterproof zippers. Instead of teeth they have kind of rails made from TPU (TRU® Zip by YKK). Highest level water protective zippers are also airtight [3]. Waterproof zippers are important and critical component of many final products used in marine industry, different sports, camping and travel gear, mobile phone accessories, others.

2.2. Quick-Release (QR) zippers

A quick-release zippers are created to open them rapidly and easily. The most often they have molded plastic teeth and specially designed their upper part or an innovative slider. The teeth of quick release zippers can be separated in two ways [6,7]:

1. Pulling the slider a little more up than normally - the user pulls the slider up to disengage and release it from one side of the zipper's teeth. When it is done a zipper opens easy by itself. (quick release zippers by YKK, KCC, SBB, Nyguard, others), (see Fig.2), [6],
2. Pulling the garment apart – specially designed asymmetrical slider of QuickFree® zipper by YKK gets released easy from one side of zipper teeth and a garment opens rapidly without moving the slider down (see Fig.3)

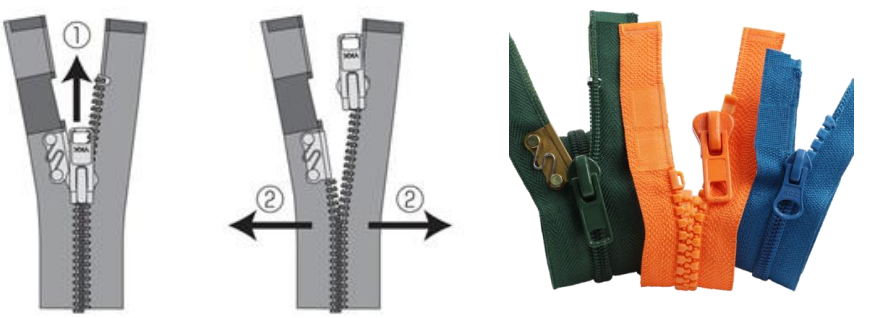

Figure 2: Quick release zippers by company KCC

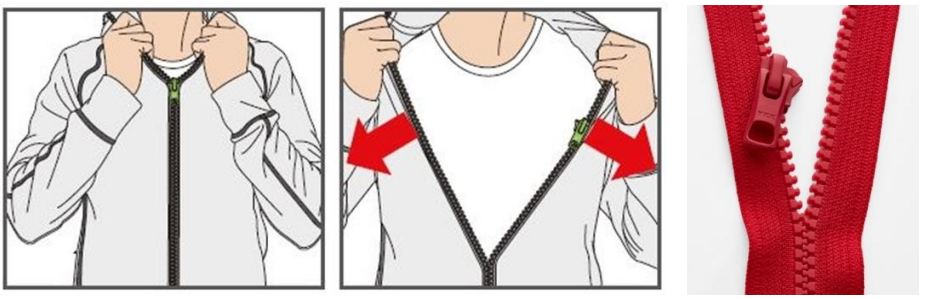

Figure 3: QuickFree® - molded separating zipper by company YKK

Often quick release zippers also have advanced closing system to ease connecting of two sides of teeth closing the zipper. Self-aligning mechanism uses small magnets inserted in the both bottom parts of a zipper (see Fig.4) [7]. Closing the zipper they join its two halves together easy without additional attention.

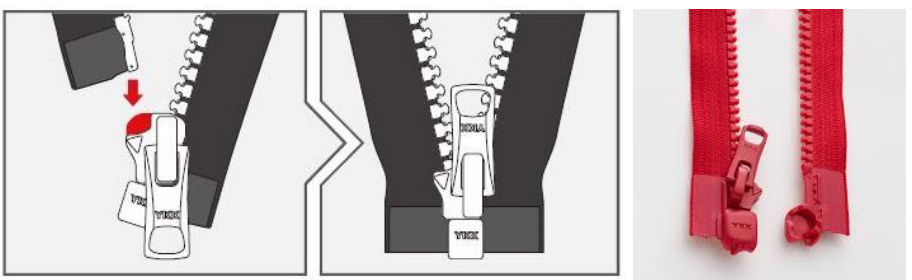

Figure 4: Click-TRAK® Magnetic by company YKK

Quick-release zippers are used for sportswear and safety clothing where quick actions are demanded. As well as, they are preferable in children, elderly and disable people garments to ease them garment taking on and off process.

2.3. Customer-repairable zippers

Zippers are very popular functional and decorative accessory used in wide variety of clothing and other textile goods. However, their repairing is almost impossible as every tooth is fixed to the tape of the zipper in special factory conditions. If only one or few teeth get damaged, the zipper has to be replaced in time and work consuming process, often reducing the original quality of the garment. As the process is complicated and also expensive, many users of the damaged textile goods decide to thrown them out, not to repair [2].

During the last decade fashion industry try to ensure the circularity of its production and extend the life cycle of textile products. Zipper companies (YKK, SBS, others) support them offering new methods to repair zippers. They have invented tools to replace broken

plastic teeth with new plastic or metal teeth in simple and easy process (see Fig.5,6), (2,8,10).

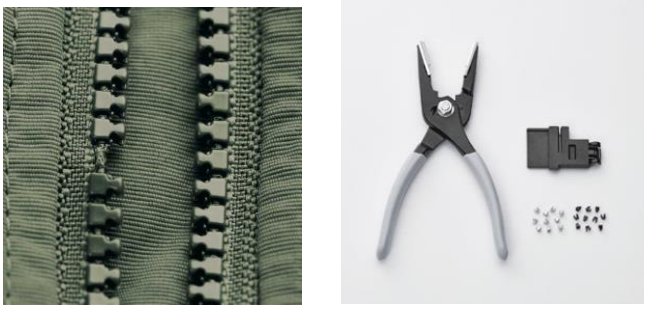

Figure 5: Repair set from special pliers, a set plate and metal teeth by company YKK

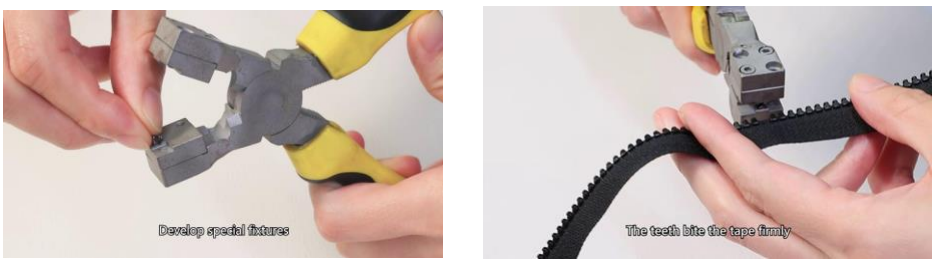

Figure 6: Mold equipment for new plastic tooth inserting by company SBS

Several companies have also developed solutions to change a damaged slider and a puller of a zipper (YKK; SBS, ZlideOn, LenZip, orhers). These parts of a zipper are specially redesigned to make possible their easy removal and replacement with new ones (see Fig.7), [2,9,1].

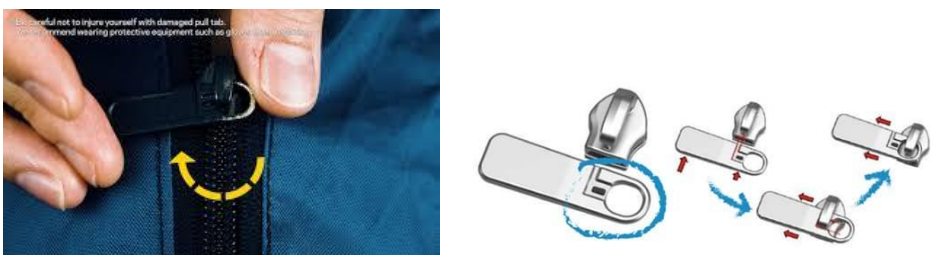

Figure 7: Replacement Puller for Coil zipper by YKK

3. SUSTAINABLE ZIPPERS

Conventional zippers are manufactured from nylon and polyester - polymers which are derived from petroleum using high energy and generating high carbon emissions. Eco-

friendly zippers are made from recycled or bio-based raw materials using low-emission coatings. Their raw materials, production methods or disposal ways support environmental protection aims (10,11,12,13).

3.1. Recycled raw materials

The most part of sustainable zippers are currently manufactured from recycled polyester or nylon. PET bottles, fishing nets, industrial scrap and textile waste are mechanical recycled, [10] melted, purified, and extruded into new filaments to created zipper tapes [11,12,14,16]. Recycled polyamide can be used to manufacture teeth, sliders and pullers of zippers [3]. Teeth of metal zippers can be made from recycled brass, stainless steel and copper. Recycled raw materials have identical structure and durability as virgin ones, their processing does not demand retooling of machinery while their use helps to reduce plastic waste and support very actual recycling efforts [2,11].

3.2. Bio-based synthetic materials

Bio-based nylon and polyester are derived from plant-based sugars, starch, cellulose, or plant oils. Company YKK is using bio-based polyester component in their GreenRise zippers [14]. It is obtained from molasses - a by-product of sugar production. Zippers of LenZip and Nyguard are manufactured from bio-based nylon which is derived from castor bean oil [12]. Mono-material and recyclable zipper Ny2Life by Italian company Nyguard is made of polyamide 6.6 [17]. The most often such zippers have teeth from bio-based materials while their tapes are made from organic cotton or other organic materials.

3.3. Organic materials

Certificated organic materials, such as cotton, linen, hump, and Lyocell are typically used manufacturing tapes of zippers. Italian company Riri (c) offers zippers with a tape from 100% organic linen (see Fig.8). Companies YKK, Lenzip and Riri use organic cotton [18]. The most often zippers from organic materials are sold unbleached in natural colour to be dyed together with a garment. They are certified by the Global Organic Textile Standard (GOTS) [19] and are used manufacturing high-end sustainable clothing.

Figure 8: Sustainable zippers with organic linen tape and stainless steel Teeth by company Riri zippers

3.4. Eco friendly finishing

Electroplating is finishing method which is traditionally used to cover metal teeth of zippers with thin metallic layer. It is done to ensure durability, corrosion resistance, and aesthetic appearance to ready zippers. However, the process is time-consuming and performed by help of hazardous and toxic chemicals. To avoid complicated finishing process many companies have started to manufacture teeth from stainless steel (SBB, YKK, Olympic zippers, Riri, others) [11,14,20]. This material is resistant to corrosion and abrasion and eliminates need to perform galvanic treatment. As the alternatives to electroplating process a company YKK uses advanced eco-friendly metal finishing methods. They use less water and energy, as well as perform metal finishing without hazardous chemicals.

4. REVOLUTIONARY ZIPPERS

Japanese company YKK is a leader in a world's market, as well as, a company which has created the most revolutionary and fully new concepts for design and functionality of zippers.

4.1. Toothless zippers

Toothless zippers Zip/Nite Ize® manufactured by YKK have two extruded TPU profiles designed like rails instead of traditional teeth. They lock together by help of ball-and-socket join mechanism (see Fig.9) and mechanical and vacuum forces (1,21).

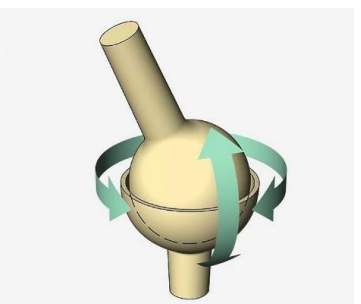

Figure 9: Ball-and-socket join mechanism

The zippers have high strength and durability and can be used for heavy duty applications (Fig.10). The closure is dustproof, airtight and fully waterproof (IP67 rated) [3]. As the zipper does not have separate teeth it cannot break like traditional zippers. If the rails accidently separate, the zipper can be easy repaired just pulling a slider back. The toothless zippers are used manufacturing waterproof travel gear, backpacks, storage bags, others.

Figure 10: Toothless zippe

4.2. Tapeless Zippers

YKK has also developed a zipper AiryString™ which does not have a tape (see fig.11). The teeth of the zipper are directly attached to the garment using a sewing machine. Such zippers are more flexible and lighter than zippers with a tape. Tapeless zippers create finerappearance to a seam in which they are inserted ensure almost invisible closure in a ready garment [2,22].

Figure 11: Upper left: Regular VISLON® zipper / Lower right: “AiryString™”

To fix a tapeless zipper into the garment, company JYKI has developed a special zig-zag stitch sewing machine. The machine is equipped with a mechanism to synchronize the feed of teeth of the zipper and the fabric during stitching process (see Fig.12) [23].

Figure 12: JUKI sewing machine for sewing “AiryString™” tapeless zippers

4.3. TouchLink® Zippers

The molded thermoplastic polyurethane puller of a YKK zipper can contain a built-in NFC chip. Tapping the smartphone against a puller of the zipper textile product manufacturers and their final users can easy get access to different kind of digital information (see Fig.13) [2]. Fashion brands can use TouchLink zippers to track manufacturing and sell process of their textile goods. In fashion business such zipper can link the brands with the users of their garments and with it to provide the valuable information used to improve new products and their sell results [2, 24].

Figure 13: Jacket with a TouchLink® zipper by Swedish sportswear brand Houdini

The puller of a Touchlink zipper can replace material content and care instructions labels, as well as, warranty registration of textile goods. It can easy keep the information of a product all its life time. The information is kept saved, even in severe weather conditions, during laundering processes or rough handling of a garment [25]. By help of the NFC chip

built-in a zipper the user of the garment could reach different apps on his smartphone, for example, music playlist or running tracker. The zipper could also keep an emergency contacts for a person with health problems or ensure his saved tracking by his family members.

In nearest future the zippers with NFC chips will help to create more sustainable fashion goods. As zipper will always keep information about the origin of materials and processes (dying, finishing) used manufacturing the textile product, it will be possible to perform its correct recycling [22].

4.4. Self-propelled zippers

In 2025 YKK announced the first prototype of a zipper with a built-in motor and gear mechanism. The zipper is developed for use in large dimension tents, shelters, banners, where very long zippers have to be inserted and their closing and opening is complicate and time consuming (Fig.14) [26,27]. If company succeeds to minimize the technology, such self –opening/closing zippers could be used also in clothing.

Figure 14: Self-propelled zippers used to close the separate part of a tent

5. CONCLUSIONS

Zipper manufacturers as a co-operators of textile good producers have to support all latest tendencies that are actual in fashion, sport and other industries which use such kind of fastening systems. Sustainable ready goods can be created if every detail in final product support sustainable manufacturing process, its use and final recycling or degradation processes. The most part of latest innovations in market, such as, the use of recycled, bio-based and organic raw materials, repairable, tapeless zippers or zippers with chips already support sustainability aims. Other important tendency in the market helps to increase comfort and functionality of ready goods with zippers. Here could be mentioned water and air proof zippers, quick release zippers, toothless and tapeless zippers, zippers with built in chips or motors. While leading Japanese company YKK is creating fully new concepts and technologies, other zipper manufacturers improve their products constantly.

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SMART WASTE HEAT RECOVERY IN TEXTILE DYEHOUSE

Professional paper
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ABSTRACT: *Textile dyehouses are among the most energy-intensive manufacturing facilities due to their high steam and hot water demand. A considerable amount of thermal energy is lost through flash steam generated in condensate return systems, which is often discharged directly to the atmosphere. This study presents an automation-assisted flash steam recovery system developed for a textile dyehouse to improve waste heat utilization and reduce steam consumption. In the proposed configuration, flash steam is recovered through a plate heat exchanger and utilized for hot water production. A PLC-based control strategy dynamically manages the recovered energy according to process requirements by switching between cold water heating and hot water boosting modes. The hot water tank is additionally utilized as a thermal energy storage unit, enabling continuous utilization of recovered energy under varying operating conditions. The results demonstrate that the proposed approach effectively reduces steam demand and carbon emissions while improving overall energy efficiency. The study highlights the potential of combining flash steam recovery, thermal energy storage and intelligent control for sustainable energy management in textile dyehouses.*

Keywords: *Flash steam recovery, Waste heat recovery, Thermal energy storage, Energy efficiency, Textile dyehouse.*

PAMETNO ISKORIŠĆENJE OTPADNE TOPLOTE U BOJADŽINICI TEKSTILA

APSTRAKT: *Tekstilne bojadžinice spadaju među industrijske pogone sa najvećom potrošnjom energije zbog visokih zahteva za parom i toplom vodom. Značajna količina toplotne energije gubi se kroz fleš paru nastalu u sistemima povrata kondenzata, koja se u većini slučajeva ispušta direktno u atmosferu. U ovom radu predstavljen je automatizovani sistem za povraćaj energije iz fleš pare razvijen za tekstilnu bojadžinicu sa ciljem povećanja energetske efikasnosti i smanjenja potrošnje pare. Predloženi sistem koristi pločasti izmenjivač toplote za proizvodnju tople vode, dok PLC zasnovana upravljačka*

strategija dinamički upravlja povraćenom energijom u skladu sa potrebama procesa. Sistem automatski prelazi između režima zagrevanja hladne vode i povećanja temperature postojeće tople vode, pri čemu rezervoar tople vode istovremeno funkcioniše kao jedinica za skladištenje toplotne energije. Rezultati pokazuju da kombinacija povraćaja energije iz fleš pare, skladištenja toplotne energije i inteligentnog upravljanja predstavlja efikasno rešenje za smanjenje potrošnje energije i emisija ugljen-dioksida u tekstilnim bojadžinicama.

Ključne reči: *Povraćaj fleš pare, Povraćaj otpadne toplote, Skladištenje toplotne energije, Energetska efikasnost, Inteligentni upravljački*

1. INTRODUCTION

The textile industry is recognized as one of the most energy-intensive manufacturing sectors due to the substantial thermal energy required during wet processing operations such as dyeing, washing, rinsing and finishing. Particularly in textile dyehouses, large quantities of steam and hot water are continuously consumed to maintain process temperatures and ensure product quality. As a result, textile wet processing accounts for a significant portion of industrial energy consumption, water usage and greenhouse gas emissions [1]. In recent years, increasing energy costs and sustainability-driven production policies have intensified the need for efficient waste heat recovery strategies capable of reducing both operational expenses and environmental impacts.

A considerable amount of thermal energy supplied to textile dyehouses is discharged through wastewater streams, condensate return systems and vented steam losses. Consequently, numerous studies have investigated heat recovery opportunities in textile processes. Early studies mainly focused on recovering sensible heat from hot wastewater through process modifications and heat exchanger integration. Kiran-Ciliz [2] demonstrated that wastewater-based heat recovery systems can significantly reduce resource consumption and annual energy costs in textile wet processing applications.

Recent studies have further improved these approaches by integrating thermal energy storage, pinch analysis and heat exchanger network optimization into textile heat recovery systems. Seo et al. [3] proposed a heated water storage-supported recovery system for textile dyeing processes, while Zuberi et al. [4] emphasized the importance of thermal energy storage for batch-operated textile systems with fluctuating thermal demand. Similarly, Kim et al. [5,6] applied pinch analysis and heat pump-assisted heat exchanger networks to optimize wastewater heat recovery systems and reported substantial reductions in energy consumption and operational costs. Although these studies provide valuable contributions regarding process integration and energy optimization, the majority of existing textile literature primarily focuses on wastewater-based heat recovery systems.

Compared with wastewater recovery applications, flash steam recovery from condensate systems has received relatively limited attention in textile-related studies. Flash steam is generated when high-pressure condensate is exposed to lower pressure conditions, causing

part of the condensate to re-evaporate. This secondary steam contains a considerable amount of recoverable thermal energy; however, in many industrial facilities it is either partially utilized or directly vented to the atmosphere due to the absence of continuous low-pressure steam demand [7,8]. Conventional flash steam recovery systems generally operate efficiently only when steam generation and process demand occur simultaneously. In batch-operated textile dyehouses, however, hot water demand varies continuously depending on production schedules, machine loading and process sequencing. Consequently, mismatches between fluctuating flash steam availability and intermittent process demand reduce overall recovery efficiency and limit the effective utilization of recovered energy.

The challenges associated with variable operating conditions have recently attracted increasing attention in industrial waste heat recovery research. Studies on dynamic waste heat recovery systems indicate that designs based solely on steady-state assumptions are insufficient for processes characterized by variable thermal loads [9]. Under such conditions, real-time monitoring, adaptive control strategies and short-term thermal energy storage become essential for improving operational stability and maximizing heat recovery performance.

Within this context, the present study proposes an automation-assisted dynamic flash steam recovery system specifically designed for textile dyehouses. In the proposed system, flash steam discharged from the condensate tank vent is separated and utilized through a plate heat exchanger for hot water production. Operational parameters such as temperature, flow rate and storage tank level are continuously monitored and controlled using temperature sensors, flowmeters and modulating control valves.

Unlike conventional flash steam recovery applications, the proposed system operates under two adaptive operating scenarios according to real-time process requirements. When hot water demand exists, cold make-up water is heated using recovered flash steam and supplied directly to the process. During periods of low or no demand, the recovered thermal energy is utilized to increase the temperature of the water already stored in the hot water tank. In this way, the storage tank functions not only as a passive reservoir but also as an active thermal energy storage unit capable of absorbing excess recovered energy.

The originality of this study lies in the integration of flash steam recovery, demand-responsive control and active thermal energy storage within a single textile dyehouse application. While previous textile studies have mainly focused on wastewater heat recovery systems and general industrial studies have investigated flash steam recovery separately [10,11], the combined implementation of condensate vent flash steam recovery with real-time automation and storage-supported energy management remains limited in the literature. Therefore, the proposed approach aims to address an important research gap by providing a flexible and scalable energy management solution capable of improving waste heat utilization, reducing steam consumption and supporting sustainable textile manufacturing practices.

2. METHOD

2.1. Conventional Condensate Handling System

The study was conducted in a textile dyehouse with an average steam consumption of approximately 2,200 tons per month. The steam system operates at a pressure of 7 bar, and condensate generated in the dyeing and washing processes is returned to the boiler house through a condensate collection network. Measurements showed that the condensate return flow rate was approximately 4 t/h, with an average condensate temperature of 90°C.

Before the implementation of the proposed system, the condensate return line discharged directly into an atmospheric condensate tank. The pressure drop between the process equipment and the condensate tank caused a portion of the condensate to flash into steam. This flash steam was continuously vented to the atmosphere through the tank vent without any heat recovery.

As a result, a significant amount of thermal energy contained in the flash steam was lost. Figures 1(a), 1(b) and 1(c) show the condensate tank vent line and the flash steam released to the atmosphere under conventional operating conditions.

(a) **(b** **(c)**

Figure 1: (a) Condensate tank vent line and (b), (c) flash steam discharged to the atmosphere before implementation of the recovery system.

2.2. Proposed Flash Steam Recovery System

To recover the thermal energy contained in the flash steam, a flash steam recovery system was installed between the condensate return line and the condensate collection tank. The proposed system consists of a flash tank, a plate heat exchanger, hot and process water storage tanks, temperature sensors, flowmeters, and PLC-controlled proportional valves.

As shown in Figure 2, condensate returning from the production processes at approximately 90°C is first directed to a flash tank with a capacity of 6 t/h. Due to the pressure reduction inside the flash tank, a portion of the condensate is separated as flash

steam. The generated flash steam is then transferred to a plate heat exchanger, where its thermal energy is utilized for water heating.
The recovery system was designed to operate under two different heating scenarios according to process requirements. In the first scenario, cold make-up water supplied from the process water tank is heated from approximately 20°C to 65°C before being transferred to the hot water tank. In the second scenario, water already stored in the hot water tank is recirculated through the heat exchanger and heated from approximately 40°C to 85°C before being returned to the tank.

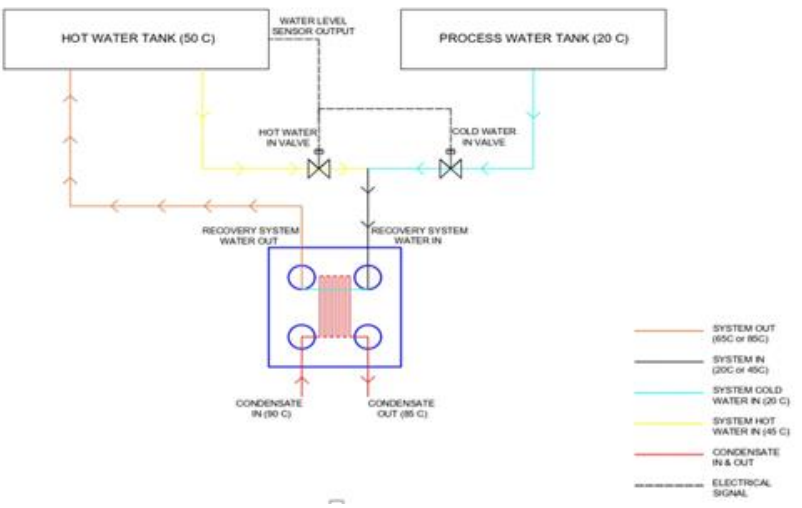

Figure 2: Schematic diagram of the proposed flash steam recovery system.

By enabling both operating modes, the system allows continuous utilization of recovered flash steam energy regardless of instantaneous hot water demand. In this configuration, the hot water tank functions not only as a storage unit but also as a thermal energy storage component capable of absorbing excess recovered energy.

2.3. Dynamic Control and Energy Management Strategy

Unlike conventional flash steam recovery systems, the proposed system was designed to operate dynamically according to real-time process conditions. A PLC-based control architecture was implemented to continuously monitor the hot water tank level, water temperatures and flow rates, and to automatically select the most appropriate operating mode.
The control strategy is based on the hot water tank level. When the tank level falls below 50%, the system operates in cold water heating mode. In this mode, make-up water

supplied from the process water tank is directed to the plate heat exchanger and heated from approximately 20°C to 65°C before being transferred to the hot water tank.
When the hot water tank level exceeds 80%, the system switches to hot water boosting mode. In this operating mode, water from the hot water tank is recirculated through the heat exchanger and heated from approximately 40°C to 85°C before being returned to the tank. This operating strategy enables the hot water tank to function as a thermal energy storage unit, allowing excess recovered energy to be stored for future process demands.
The outlet water temperature is continuously regulated through PLC-controlled proportional valves. Temperature measurements obtained from PT100 sensors are used as feedback signals to maintain the desired outlet temperature setpoint. Variations in flash steam generation caused by changes in condensate flow rate or production conditions are automatically compensated through valve modulation, ensuring stable system operation without operator intervention.
As a result, the developed control strategy enables continuous utilization of flash steam energy under varying production conditions while maximizing energy recovery efficiency and minimizing thermal energy losses.

2.4. Energy Recovery Calculation

The recovered thermal energy was calculated based on the measured water flow rates and temperature differences across the heat exchanger. The amount of recovered heat was determined using Equation (1):

$$Q = m \cdot c_P \cdot \Delta T \quad (1)$$

where Q is the recovered thermal energy (kJ), m is the mass of heated water (kg), c_p is the specific heat capacity of water (4.18 kJ/kg·°C), and ΔT is the temperature increase across the heat exchanger (°C).
The total recovered energy was calculated separately for the cold water heating mode and the hot water boosting mode and subsequently combined to determine the overall system performance. The equivalent steam savings were calculated by dividing the recovered thermal energy by the latent heat of saturated steam at the operating pressure of 7 bar, which was taken as 2050 kJ/kg [12].
In addition, the reduction in carbon emissions was estimated based on the annual steam savings achieved by the proposed recovery system. The calculated energy recovery, steam savings and emission reduction values were used to evaluate the technical performance of the developed flash steam recovery and energy management system.

3. RESULTS

3.1. Energy Recovery Performance

The proposed flash steam recovery system successfully utilized the thermal energy contained in the flash steam generated from the condensate return system. The recovered energy was used in two different operating modes: cold water heating and hot water boosting.

During the monitoring period, approximately 2,398 m³ of cold make-up water was heated from 20°C to 65°C, while 4,552 m³ of water from the hot water tank was heated from 40°C to 85°C. The corresponding energy recovery values are presented in Table 1.

Table 1: Energy recovery performance of the proposed system

Parameter	Value
Cold water heated (m³/month)	2,398
Hot water heated (m³/month)	4,552
Cold water heating energy recovery (kJ/month)	451,063,800
Hot water boosting energy recovery (kJ/month)	856,231,200
Total recovered energy (kJ/month)	1,307,295,000

The results indicate that the proposed system recovered approximately 1.31×10^9 kJ of thermal energy per month. Furthermore, approximately 65.5% of the total recovered energy was obtained during the hot water boosting mode. This finding highlights the importance of utilizing the hot water tank as a thermal energy storage unit. Without the storage-assisted operating mode, a significant portion of the recovered flash steam energy would remain unused during periods of low hot water demand.

3.2. Steam Saving Potential

To evaluate the impact of the recovered energy on boiler operation, the total recovered energy was converted into equivalent steam savings using the latent heat of saturated steam at 7 bar operating pressure (2050 kJ/kg).
The results are summarized in Table 2.

Table 2: Equivalent steam savings achieved by the proposed system

Parameter	Value
Latent heat of steam at 7 bar (kJ/kg)	2,050
Equivalent steam saving (ton/month)	638
Equivalent steam saving (ton/year)	7,652

The recovered thermal energy corresponds to approximately 638 tons of steam savings per month, equivalent to 7,652 tons annually. Considering that the facility consumes approximately 2,200 tons of steam per month, the proposed system reduced steam demand by nearly 29%.
This result demonstrates that flash steam discharged from condensate systems represents a substantial energy recovery opportunity in textile dyehouses. The achieved steam savings are particularly significant because they were obtained without modifications to the production process itself and solely through the recovery and intelligent management of waste thermal energy.

3.3. Environmental Impact and System Evaluation

The reduction in steam generation requirements directly decreased fuel consumption and associated greenhouse gas emissions. Based on the annual steam savings, the proposed system achieved an estimated reduction of 2,437 tons of CO_2 emissions per year.

Table 3: Environmental benefits of the proposed system

Parameter	Value
Annual steam saving (ton/year)	7,652
Annual CO_2 reduction (ton/year)	2,437

Beyond the energy and environmental benefits, the developed system demonstrated stable operation under varying production conditions. The PLC-based control architecture continuously adjusted the operating mode according to hot water tank level and process requirements, ensuring that recovered flash steam energy was continuously utilized. The use of proportional control valves and temperature feedback from PT100 sensors enabled automatic compensation for fluctuations in flash steam generation without operator intervention.

Compared with conventional flash steam recovery applications, which typically depend on simultaneous heat demand, the proposed approach increased energy utilization by integrating dynamic control with thermal energy storage. This configuration minimized energy losses during low-demand periods and enabled continuous recovery of flash steam energy throughout plant operation.

4. CONCLUSION

This study demonstrated the feasibility of recovering flash steam energy from condensate tank vents in textile dyehouses through an automation-assisted energy management system. The proposed configuration combined flash steam recovery, thermal energy storage and dynamic process control within a single integrated framework.

The system recovered approximately 1.31×10^9 kJ of thermal energy per month, corresponding to an equivalent steam saving of 638 tons per month or 7,652 tons annually. Considering the facility’s average monthly steam consumption of 2,200 tons, the recovered energy reduced steam demand by approximately 29%.

The results also showed that a significant portion of the recovered energy was utilized during the hot water boosting mode, demonstrating the effectiveness of using the hot water tank as a thermal energy storage unit. This approach enabled continuous utilization of flash steam energy even during periods of low process demand, thereby minimizing energy losses.

In addition to the energy savings, the proposed system achieved an estimated annual reduction of 2,437 tons of CO_2 emissions, contributing to the sustainability objectives of textile manufacturing. The PLC-based control architecture ensured fully automatic

operation and maintained stable performance under varying process conditions without requiring operator intervention.

Overall, the proposed approach offers a practical and scalable solution for improving energy efficiency in textile dyehouses by transforming an often-vented waste energy stream into a continuously usable thermal energy source through intelligent energy management.

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INTEGRATION OF BIOACTIVE COMPONENTS INTO UPHOLSTERY FABRICS VIA MICROENCAPSULATION METHOD FOR THE CONTROL OF CAT SCRATCHING BEHAVIOR

Scientific paper
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ABSTRACT: *Scratching of household furniture by cats is a common issue reported by pet cargivers. Various studies have been conducted worldwide to reduce the frequency of scratching and mitigate its undesirable consequences. Inappropriate scratching not only causes damage to household items but may also lead to deterioration of the human–animal bond and even abandonment of cats. This study aims to reduce the damage to upholstery fabrics in home environments and to control the scratching behavior of domestic cats by integrating bioactive components into textile surfaces through microencapsulation technology. Within the scope of the study, microcapsule structures will be developed containing citrus-based essential oils that act as natural repellents, as well as cat pheromones used to direct cats toward designated scratching areas. In order to ensure both sustainability and textile compatibility, the complex coacervation technique has been employed, utilizing natural biopolymers such as β-cyclodextrin and gum arabic as shell materials. This method is based on sensitive electrostatic interactions between oppositely charged polymers, controlled via pH adjustment, to form a protective shell around the dispersed core material. The microcapsule production protocol consists of four systematic stages:*

-Formation of a stable water-in-oil emulsion,
-Initiation of polymer complexation,
-Deposition of the coacervate phase onto the core material, and

-Stabilization of the capsule wall structure using a crosslinking agent.
Our evaluations indicate that pH, stirring speed, and the sequence of component addition are the most critical parameters in achieving structural homogeneity. To verify the success of the synthesis, the microcapsules were analyzed using optical microscopy in terms of morphological integrity. Particle size distribution determined by laser diffraction confirmed that target capsules with high homogeneity and sizes of 10 µm or smaller were successfully obtained. Furthermore, after application onto the fabric, the distribution of the capsules was examined by SEM, their presence within the polyester structure was confirmed by FT-IR analysis, and their release behavior was evaluated using GC-MS. These optimized formulations will be scaled up in subsequent stages of the study, and field studies will be conducted to investigate their effects on cat scratching behavior. This study is carried out under Project No. 5240101 (TÜBİTAK 1505 – University-Industry Collaboration Support Program) in cooperation with Aydin Mensucat Dosemelik Kumas San. ve Tic. A.S (Sakarya).

Keywords: *Microencapsulation, coacervation method, essential oil, cat scratching.*

INTEGRACIJA BIOAKTIVNIH KOMPONENTI U TKANINE ZA TAPACIRANJE METODOM MIKROENKAPSULACIJE RADI KONTROLE GREBANJA MAČAKA

APSTRAKT: *Grebanje kućnog nameštaja od strane mačaka je čest problem koji prijavljuju vlasnici kućnih ljubimaca. Različite studije su sprovedene širom sveta kako bi se smanjila učestalost grebanja i ublažile njegove neželjene posledice. Neprikladno grebanje ne samo da oštećuje kućne predmete, već može dovesti i do pogoršanja veze između ljudi i životinja, pa čak i napuštanja mačaka. Cilj ove studije je smanjenje oštećenja tapacirunga u kućnim okruženjima i kontrola ponašanja grebanja domaćih mačaka integrisanjem bioaktivnih komponenti u tekstilne površine putem tehnologije mikroenkapsulacije. U okviru studije, biće razvijene strukture mikrokapsula koje sadrže eterična ulja na bazi citrusa koja deluju kao prirodni repelenti, kao i mačje feromone koji se koriste za usmeravanje mačaka ka određenim mestima za grebanje. Da bi se osigurala i održivost i kompatibilnost sa tekstilom, korišćena je tehnika kompleksne koacervacije, koristeći prirodne biopolimere kao što su β-ciklodekstrin i guma arabika kao materijale za omotač. Ova metoda se zasniva na osetljivim elektrostatičkim interakcijama između suprotno naelektrisanih polimera, kontrolisanih podešavanjem pH vrednosti, kako bi se formirao zaštitni omotač oko dispergovanog materijala jezgra. Protokol proizvodnje mikrokapsula sastoji se od četiri sistematske faze:*
- Formiranje stabilne emulzije voda-u-ulju,
- Pokretanje polimerne kompleksizacije,
- Taloženje koacervatne faze na materijal jezgra i
- Stabilizacija strukture zida kapsule upotrebom sredstva za umrežavanje.

Naše evaluacije pokazuju da su pH, brzina mešanja i redosled dodavanja komponenti najkritičniji parametri u postizanju strukturne homogenosti. Da bi se potvrdio uspeh sinteze, mikrokapsule su analizirane optičkom mikroskopijom u smislu morfološkog integriteta. Raspodela veličine čestica određena laserskom difrakcijom potvrdila je da su uspešno dobijene ciljne kapsule sa visokom homogenošću i veličinama od 10 µm ili manje. Štaviše, nakon nanošenja na tkaninu, distribucija kapsula je ispitana SEM-om, njihovo prisustvo unutar poliestarske strukture je potvrđeno FT-IR analizom, a njihovo ponašanje pri oslobađanju je procenjeno pomoću GC-MS. Ove optimizovane formulacije će biti povećane u narednim fazama studije, a biće sprovedene i terenske studije kako bi se ispitao njihov uticaj na ponašanje mačke pri grebanju. Ova studija se sprovodi u okviru projekta br. 5240101 (TÜBİTAK 1505 – Program podrške saradnji univerziteta i industrije) u saradnji sa Aydin Mensucat Dosemelik Kumas San. ve Tic. A.S (Sakarija).

Ključne reči: *Mikroenkapsulacija, metoda koacervacije, eterično ulje, mačje grebanje.*

1. INTRODUCTION

The increasing demand for enhanced functionality and multi-functional textile materials has shifted research efforts toward textile production based on multidisciplinary approaches. The focal point of these research activities is the concept of sustainable manufacturing. Numerous processes, machinery, and chemicals are being developed to reduce water, chemical, energy, and waste consumption at every stage of textile production, starting from the raw material. Reducing the environmental waste load of the chemicals used is another key area of investigation. Microencapsulation technology, which has been studied for many years and utilized in numerous fields such as agriculture, medicine, food processing, cosmetics, and the chemical industry, has also become widespread in the textile sector. It has gained particular importance in applications where high durability and permanence are required [1,2].

A microcapsule consists of a polymeric shell and an active substance in solid, liquid, or gaseous form placed inside this shell. The microencapsulation of a material provides numerous advantages, such as protection against external factors like moisture, oxygen, and chemical substances [3] taste and odor masking; holding liquids in solid form; the controlled transport of hazardous liquids; and controlled release capability [4] This technology also enables liquids that are particularly difficult to transfer onto materials, such as oils, to interact with the material. Microcapsule solutions are applied to the material via methods like padding, dipping, and coating. The release of the active ingredient occurs when the outer shell ruptures due to various external influences like pressure, temperature, or chemicals, or through diffusion based on the properties of the shell material.

Both synthetic and natural polymers can be used as microcapsule outer shell materials. Natural polymers (chitin and chitosan, alginate, dextran, cellulose, starch, gelatin, gum arabic, agar, pectin, casein, etc.) are preferred due to their stability and controllable size distribution. On the other hand, synthetic polymers (polylactic acid, polyglycolic acid,

polyamino acids, polycaprolactone, vinyl derivatives, polycarbonate, acrylic polymers, polyamides, polyurethanes, polyanhydrides, cellulose derivatives, etc.) are preferred because they can be prepared according to desired conditions, remain durable during preparation and storage periods, and can be produced with high purity.
There are numerous methods available for obtaining microcapsules. These are categorized into chemical microencapsulation methods (such as in-situ polymerization and interfacial polymerization), physical microencapsulation methods (such as spray drying, solvent evaporation, and extrusion), and physicochemical microencapsulation methods (such as coacervation and molecular inclusion). The morphology of the microcapsules can vary depending on the applied methods (Figure 1).

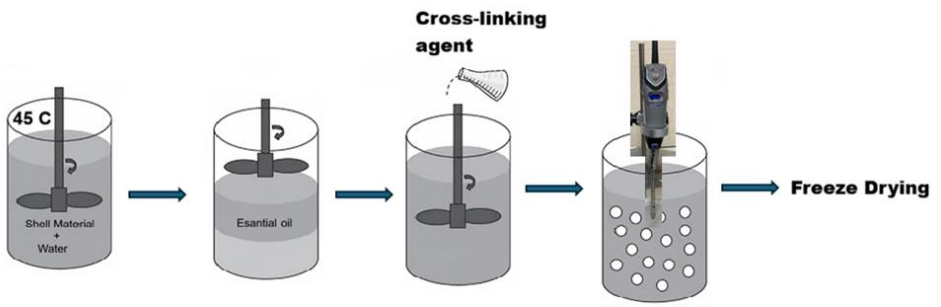
Figure 1. Microcapsules with different morphological structures [5]

Within the scope of this study, phase separation (simple and complex coacervation) and molecular inclusion (with cyclodextrins) methods, which are classified under physicochemical microencapsulation methods, were employed. Although these methods are advantageous because they allow the use of safer and eco-friendly shell materials, their most significant disadvantage is their low resistance to physical factors. In the coacervation method, the core material is dispersed within the polymer solution. The shell material is formed by inducing phase separation through altering the solubility of the polymer solution via cooling during stirring, changing the pH, creating an ionic gradient, etc. Many natural polymers are suitable for this method. This technique is examined under two groups: aqueous and organic phase separation. Aqueous phase separation is further divided into simple and complex coacervation [6].
Cyclodextrins are cyclic oligosaccharides containing at least six D-(+)-glucopyranose units linked by α(1,4)-glucosidic bonds. With their lipophilic internal cavities and hydrophilic external surfaces, they can interact with various guest molecules to form non-covalently bound inclusion complexes that provide protection and enhance solubility, biocompatibility, and stability [7].
In residential living areas, pet care has become one of the most prominent human activities. However, scratching behavior, especially by cats on household items, is a common issue complained about by pet caregivers. Various studies are being conducted worldwide to reduce the frequency of scratching and to mitigate its undesirable outcomes. While

inappropriate scratching causes damage to household goods, it is also a significant reason for the breakdown of the human-animal bond and ranks as the second leading cause of cat abandonment. Destructive targeting of household furniture, a behavior characterizing unwanted scratching, poses a significant threat to cat welfare and often leads to misperceptions and improper interventions in domestic environments [8] Inappropriate scratching is perceived as a problem by some cat caregivers because it can damage household items such as chairs, furniture, carpets, sofas, doors, walls, and curtains [9].
The objective of this study was to gather data regarding the scratching behaviors of domestic cats and to determine their preferred fabric types for scratching. In this context, lime essential oil (citrus-based), which is thought to be repellent to cats, and pheromone essential oil, which is thought to attract cats, were encapsulated using the simple coacervation method and subsequently transferred onto a selected polyester-based upholstery fabric. In the subsequent stages of the study, cat behaviors will be observed via field studies.

2. EXPERIMENTAL

In this study, microcapsule preparation and characterization trials were carried out according to the coacervation and inclusion methods. Beta-cyclodextrin (Glentham), gum arabic (ZAG), polystyrene maleic acid sodium salt (Sigma), sodium dodecyl benzene sulfonate (SCBT), tannic acid (Therma-Alfa), glutaraldehyde 50% (Tekkim-4), sodium sulfate (AFG Bio), PH-052-1-K Lime oil (Pharmaterm), and oil containing pheromone (Feliway classic diffuser, Ceva) were used for microcapsule synthesis. The workflow diagram applied in the study (Figure 2) and the recipes are given below Table 1.



Mechanical Stirring Stirring in a homogenizer

Figure 2. Process steps for microencapsulation preparation

Table 1: Chemicals and working conditions used for microcapsule preparation.

Recipes (Shell/Core)*	Working Conditions
β-Cyclodextrin/ Lime Oil	β-Cyclodextrin by stirring 45 ºC Lime oil

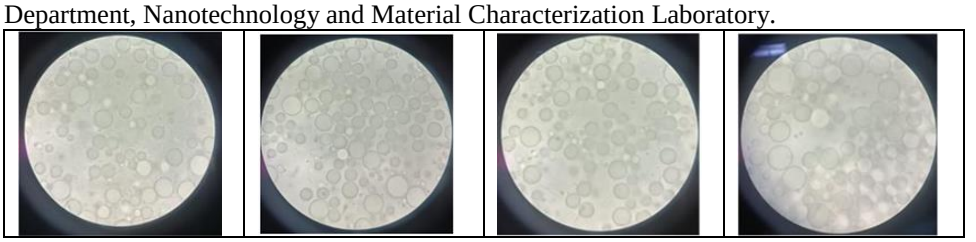
	Polystyrene maleic acid Na salt Sodium dodecyl benzene sulfonate (Surfactant) Tannic acid Stirring speed: 800 rpm, Stirring time: 15 minutes, pH 4.5 Stirring in a homogenizer at 14,000 rpm for 3 minutes Freeze Drying
Gum Arabic/ Lime Oil	Gum arabic by stirring at room temperature Lime oil Sodium sulfate Glutaraldehyde (50%) (Cross-linking agent) Stirring speed: 1500 rpm, pH 5.5 - 6 Stirring in a homogenizer at 14,000 rpm for 3 minutes Freeze Drying
Gum Arabic / Oil Containing Pheromone	Gum arabic by stirring at room temperature Oil Containing Pheromone Sodium sulfate Glutaraldehyde (50%) (Cross-linking agent) Stirring speed: 1500 rpm, pH 5.5 – 6 Stirring in a homogenizer at 14,000 rpm for 3 minutes
β-Cyclodextrin/Oil Containing Pheromone	β-Cyclodextrin by stirring 45 ºC Oil Containing Pheromone Polystyrene maleic acid Na salt (Anionic polymeric dispersant) Sodium dodecyl benzene sulfonate (Surfactant) Tannic acid Stirring speed: 800 rpm, Stirring time: 15 minutes, pH 4.5 Stirring in a homogenizer at 14,000 rpm for 3 minutes Freeze drying

** In all formulations, the shell/core material ratio was kept at 1:2*

The prepared solutions were transferred onto a polyester upholstery fabric was produced using a combination of polyester yarns with different denier and functional characteristics. The warp direction consisted of 300 denier polyester (PES) intermingled yarn and 620 denier/16 filament polyester intermingled anionic/cationic yarn. The weft direction comprised 300 denier DTY polyester intermingled yarn and 810 denier T/N cationic intermingled yarn. The resulting fabric exhibited an areal density of 286 g/m².Prior to dyeing, the fabric was subjected to NaOH-based chemical surface treatment followed by physical surface abrasion. Subsequently, the fabric was dyed to achieve the desired coloration. The study was executed with a 100% wet pick-up (liquor absorption ratio). Following the transfer process, the fabrics were dried at 80 °C for 5 minutes and cured (fixed) at 120 °C for 3 minutes.

3. RESULTS AND DISCUSSION

Following the application, light microscopy images were captured for all samples.
Particle size and distribution analyses of the obtained solutions were conducted using the particle size analyzer at the Bursa Uludağ University (BUU) Textile Engineering Department, Nanotechnology and Material Characterization Laboratory.



(a) **(b)** **(c)** **(d)**

Figure 3. Light microscopy images: **(a)** β-Cyclodextrin/Lime Oil, **(b)** Gum Arabic – Lime Oil, **(c)** Gum Arabic - Oil Containing Pheromone, **(d)** β-Cyclodextrin - Oil Containing Pheromone.

3.1. Particle Size Analysis

Looking at the data for the **β-Cyclodextrin / Lime oil** solution, the average volumetric particle size was around 11.72 µm, with the smallest particles at 2.48 µm and a median value of approximately 5.60 µm. The average size being significantly higher than the median value suggests the presence of larger particles or agglomerations that skew the average distribution. The most common particle size (mode) observed in the measured sample was 6.25 µm. The standard deviation was calculated as 26.1858 µm; this high deviation indicates that the particle sizes span a wide range and the distribution within the sample is not highly homogeneous.

Median size	: 5.60399 (µm)	D(v,0.1) :	2.48666 (µm)
Mean size	: 11.72130 (µm)	D(v,0.5) :	5.60399 (µm)
Variance	: 685.70 (µm^2)	D(v,0.9) :	14.10352 (µm)
St. Dev.	: 26.1858 (µm)		
Mode size	: 6.2474 (µm)		
Span	: Off		
Geo. mean size	: 6.2137 (µm)		
Geo. variance	: 1.3911 (µm^2)		
D10	: 2.48666 (µm)		
D90	: 14.10352 (µm)		

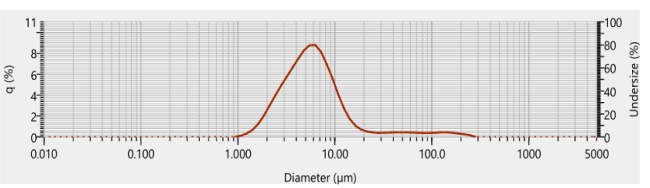


Figure 4. Particle size analysis graph for β-Cyclodextrin / Lime oil solution

The graph for the **Gum Arabic /Lime Oil solution** clearly exhibits a bimodal (two-peaked) distribution. The median value of 12.83 µm indicates that 50% of the particles by volume are smaller and 50% are larger than this value. The mean size of 38.51 µm confirms the presence of large particles within the structure, while the mode value of 12.41 µm represents the most frequently encountered particle size in the sample. These values demonstrate that the distribution is heterogeneous.

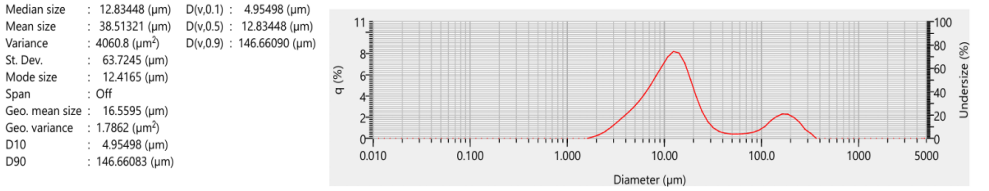


Figure 5. Particle size analysis graph of gum arabic / lime oil solution

Analyzing the data for the **Gum Arabic / Oil Containing Pheromone** solution, the distribution appears more controlled, yet it indicates the presence of large clusters within the particle size spectrum (Figure 6). In this sample, the median was 18.93 µm, the mean size was 32.36 µm, and the mode was 18.69 µm. Looking at the span width, D10 (7.53 µm) shows that the smallest 10% fraction is below 7.5 µm, while D90 (48.97 µm) reveals that the largest 10% fraction is greater than approximately 49 µm. A relatively more homogeneous structure was observed in terms of particle size compared to the lime oil recipes.

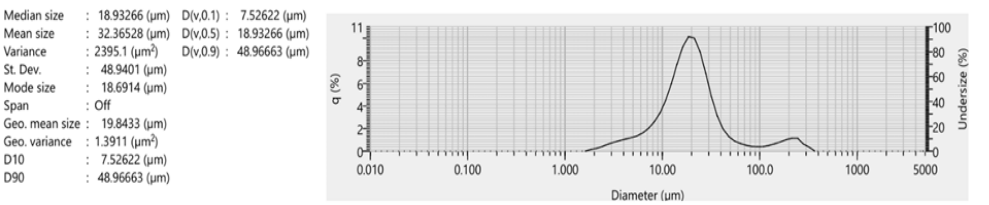


Figure 6. Particle size analysis graph of gum arabic- Oil Containing Pheromone solution

The formulation for **β-Cyclodextrin - Oil Containing Pheromone** yielded the most homogeneous and narrowest distribution among all trials. In this recipe, the median was 13.57 µm, the mean size was 15.40 µm, and the most frequently encountered particle size (mode) was 14.16 µm. Approximately 80% of the sample accumulated within the 6.27 and 26.06 µm range. Variance and standard deviation values were lower than those of the other analyses, confirming a significantly more homogeneous distribution.

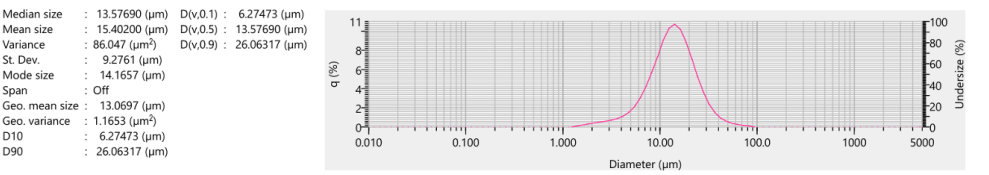


Figure 7. Particle size analysis graph of β-Cyclodextrin- Oil Containing Pheromone solution

3.2. Scanning Electron Microscopy (SEM) Analyses

SEM analyses were carried out as a commercial service using the Zeiss Gemini SEM analytical device located at the Bursa Technical University (BTU) Central Research Laboratory (MERLAB).

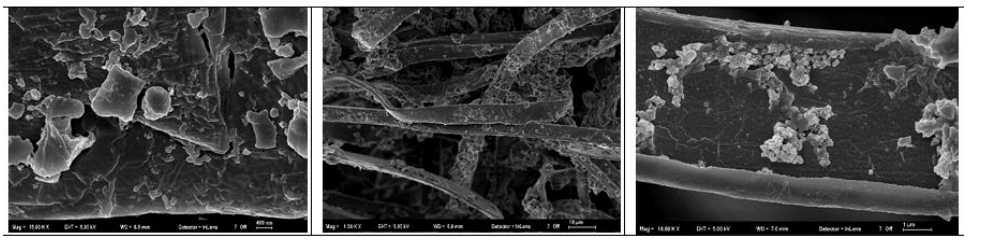


Figure 8. SEM Analysis of PET Fabric applicated with β-Cyclodextrin / Lime oil Microencapsulation Solution

β-Cyclodextrin / Lime oil: The SEM analysis shows numerous irregularly shaped microcapsules and aggregates (clumps) clustered on and between the fibers. In the middle and upper-right regions of the fibers, the capsules formed larger clusters. It is evaluated that this behavior might stem from the capsules preferring to adhere in particulate form rather than forming a homogeneous film on the fiber surface during the padding process.

Gum Arabic / Kaffir Lime: The SEM analysis reveals a large number of small nanoparticles and island-like clusters formed by these particles on the fiber surface. It can be predicted that gum arabic encapsulates the kaffir lime essential oil not only at the micron scale but also at the nanometer scale. These nano-scale structures could enhance the effective dissipation of the scent by increasing the total surface area. The particles appear to be tightly bound and well-integrated into the fiber surface. Compared to the structures observed in the β-Cyclodextrin shell, gum arabic displays a more amorphous morphology with spherical aggregates (Figure 9).

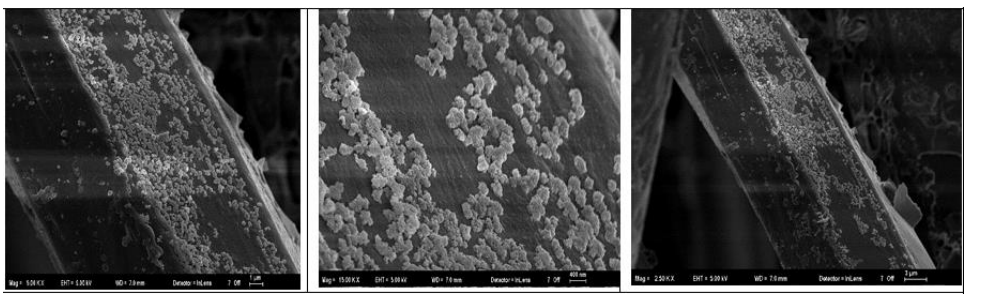


Figure 9. SEM Analysis of PET Fabric applicated with Arabic Gum/Lime Oil Microencapsulation Solution

Gum Arabic / Oil Containing Pheromone: The SEM analysis demonstrates that the microcapsule solution (gum arabic matrix) envelops the polyester fibers like a sheath, creating a smooth film layer.

Figure 10. SEM analysis of fabric treated with gum arabic- Oil Containing Pheromone solution.

β-Cyclodextrin / Oil Containing Pheromone: Figure 11 shows that the fiber surface is quite dense, with some areas of roughness, and covered with nanometer-scale particles. The β-cyclodextrin complex has penetrated the fibers and their indentations and protrusions, forming an integrated structure. Numerous small, spherical formations adhering to the fiber surface are visible in the image. These are β-cyclodextrin microcapsules that trap the pheromone.

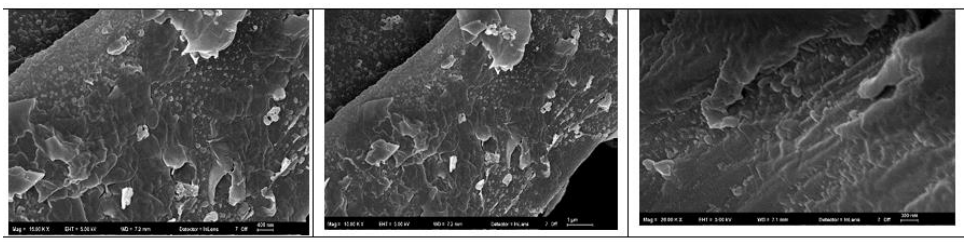


Figure 11. SEM analysis of fabric applicated with β-cyclodextrin- Oil Containing Pheromone solution

3.3. Gas Chromatography-Mass Spectrometry (GC-MS) Analyses

GC-MS analyses were performed at the **Rudolf-Duraner (Bursa)** facility. In **Figure 12**, chromatograms (e) and (f) represent the pure Musk Lemon and Oil Containing Pheromone, respectively. Chromatograms (a), (b), (c), and (d) correspond to the polyester fabrics onto which the formulations were applied.

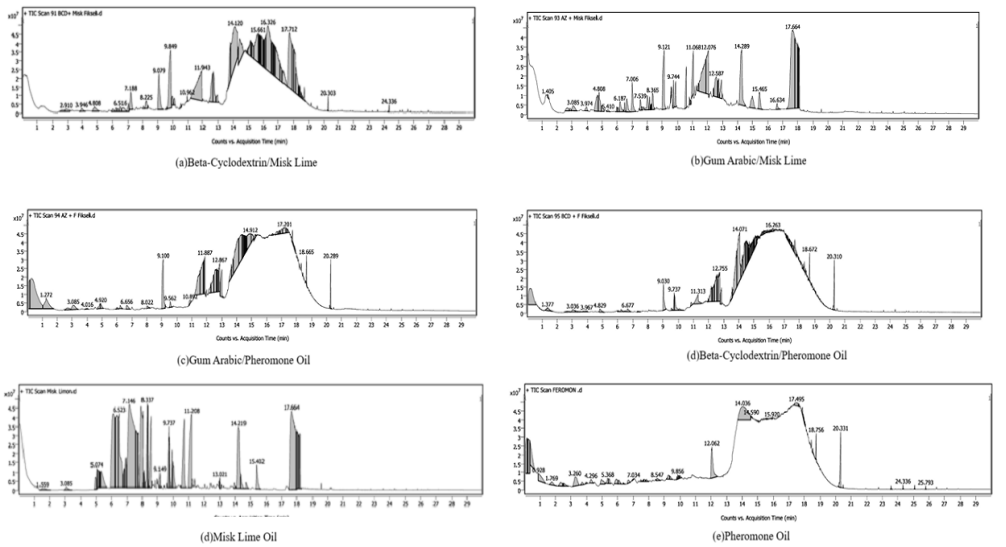


Figure 12. GC-MS Analyses

(a): β-cyclodextrin / Lime Oil Solution: When chromatogram (a) is examined, it is observed that:

- The peaks in the **0–5 minute range** belong to low-intensity and highly volatile components.
- The peaks in the **9–13 minute range** belong to highly distinct major aroma components.
- The sharp peaks in the **14–18 minute range** correspond to the behavior of an encapsulated system rather than a conventional essential oil.

Here, it can be inferred that there is a coexistence of numerous overlapping components rather than a single compound, exhibiting a diffusion-controlled release character. This behavior generally suggests compatibility with β-cyclodextrin complexes.

(b): Gum Arabic / Lime Oil Solution: In chromatogram (b), it is observed that the main structure is preserved between **14 and 17 minutes**. This indicates that the microcapsule structure was successfully fixed onto the fabric during the curing process. Gum arabic is a polysaccharide. Characteristic furfural and sugar-derivative structures resulting from thermal degradation (pyrolysis) may have increased the peak intensity in the mid-to-late region (**10–15 min**). The most intense region, featuring peaks at **14.630, 16.353, and 17.502 minutes**, is evaluated as the primary degradation products of the polyester (PET) and the capsule wall. The uniformity of this region indicates that the capsules are homogeneously embedded between the fabric fibers and that the matrix (capsule-fabric) behaves as a single integrated unit.

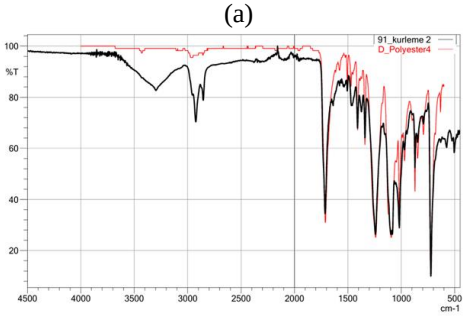
(c): Gum Arabic / Oil Containing Pheromone: The peaks between **1 and 10 minutes** in the GC-MS chromatogram given in Figure 12 (c) represent the pheromone components. Microencapsulating the pheromone using gum arabic demonstrates success in terms of both adhesion to the polyester fabric and enhancing the thermal stability of the pheromone.
(d): β-cyclodextrin / Oil Containing Pheromone: When the chromatogram in (d) is examined, the peak where the main components are released is observed in the **13–18 minute range**. Looking at the distribution in the graph, it can be stated that the pheromone structure exhibits lower volatility and later elution. The primary region in pheromone encapsulation is observed within the range of **~14.07 – 16.26 min**, where the highest intensity occurs. This indicates that the main fraction of the pheromone active ingredients is located here.
(e) and (f): Pure Oils: Chromatograms of the pure oils were also obtained, where (e) and (f) represent the pure essential oils:

- **Lime oil (e):** Numerous sharp peaks are clustered within the **first 7 minutes**. This region represents monoterpenes such as Limonene, Citral, Terpinene, and Pinene, which give the lemon its characteristic scent. The peak at **9.096 min** emerges as the common major component present in both the oil containing pheromone and the musk lemon essence. Its dominance in the essential oil indicates that this molecule is a fixative (scent carrier) component. The fact that this peak remains unchanged in the pure oil, the microcapsule solution, and on the fabric demonstrates its chemical stability. This confirms that the scent component can be successfully integrated into the polyester fabric structure.
- **Oil Containing Pheromone (f):** When the GC-MS chromatogram is examined, the peak at **9.098 minutes** is the most dominant active substance of the oil. This overlaps with the peak observed in the same range in previous chromatograms. This can be considered evidence that the pheromone was successfully entrapped within the microcapsule and maintained its character on the fabric.

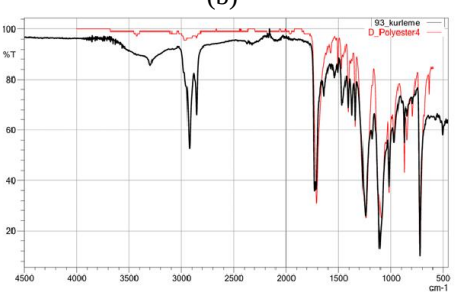
3.4. Fourier-Transform Infrared Spectroscopy (FT-IR) Analyses

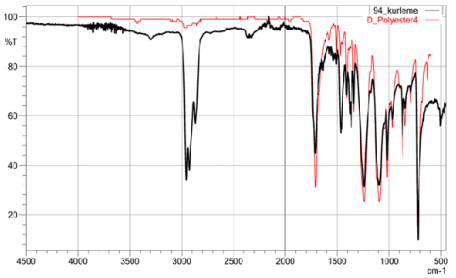
FT-IR analyses were performed at the BUÜ (Bursa Uludağ University) Nanotechnology and Material Characterization Laboratory.

(a)

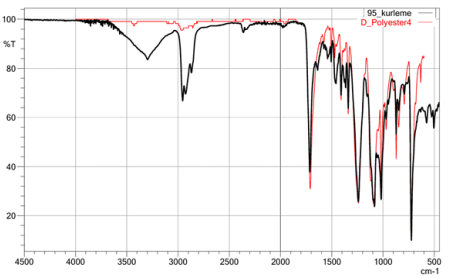


(b)





(c)



(d)

Figure 13. FT-IR analysis spectra of fabrics applied with microcapsule formulations: (a): β-cyclodextrin / Lime Oil, (b): Gum Arabic / Lime Oil, (c): Gum Arabic / Oil Containing Pheromone, (d): β-cyclodextrin / Oil Containing Pheromone

(a): β-cyclodextrin / Lime Oil: When evaluating the curve given in **Figure 13 (a)**, a wide and deep absorption band is observed at **3300 cm⁻¹**, which distinguishes it from the baseline PET spectrum.

- This region is attributed to the **–OH groups** present in the structure of β-cyclodextrin.
- The broad nature of these peaks indicates that the β-cyclodextrin molecules form hydrogen bonds both among themselves and with the components of the musk lemon oil.
- The peaks observed at **2924 cm⁻¹** and **2950 cm⁻¹** belong to aliphatic **–CH stretching vibrations**. These peaks are considered to originate from the carbon chains of the musk lemon essential oil entrapped within the hydrophobic cavity of β-cyclodextrin.

(b): Gum Arabic / Lime Oil: In diagram (b), corresponding to the fabric treated with the Gum Arabic / Lime solution:

- The broad band observed at **3300 cm⁻¹** indicates that a portion of the free hydroxyl groups became bound during the thermal treatment, confirming that the capsules adhered to the fabric surface.
- The peaks observed at **2923 cm⁻¹** and **2853 cm⁻¹** demonstrate the presence of hydrocarbon chains from the musk essential oil within the structure.
- This indicates that the scent component did not leave the system during the curing process, demonstrating the barrier effect of gum arabic. The fragrance component remains successfully entrapped within the polymeric matrix.
- The peak emerging at **1025 cm⁻¹** belongs to the polysaccharide backbone (**–C–O–C– bonds**) of the gum arabic.

(c): Gum Arabic / Oil Containing Pheromone: In the fabric treated with the Gum Arabic / Oil Containing Pheromone (c):

- The peaks at **2924 cm⁻¹** and **2853 cm⁻¹** appear much more prominent and correspond to the primary carbon backbone of the pheromone. This clearly

confirms the presence of the gum arabic–pheromone microcapsule structure on the fabric.

- The intense peak around **1025 cm⁻¹** is a region that is absent in the reference PET (red) spectrum but is highly pronounced in the sample. This region corresponds to the **C–O–C glycosidic bonds** in the polysaccharide structure of gum arabic.
- The intensity of this region demonstrates that the fabric surface is completely coated with a Gum Arabic matrix that encapsulates the pheromone.

(d): β-cyclodextrin / Oil Containing Pheromone: The final spectrum (d) belongs to the fabric treated with the β-cyclodextrin / Oil Containing Pheromone:

- Distinct from the untreated PET fabric, the two sharp peaks observed at **2924 cm⁻¹** and **2853 cm⁻¹** are the **C–H stretching peaks** belonging to the long aliphatic carbon chains of the pheromone.
- The presence of these peaks in the spectrum indicates that the structure was successfully entrapped within the CD cavity and remained within the structure after the curing process.
- The peaks at **1026 cm⁻¹** and **1078 cm⁻¹** also deviate from the reference PET spectrum. These peaks demonstrate that β-cyclodextrin accommodated the pheromone, adhering to the fabric surface as a **host-guest complex**.

4. CONCLUSION

In this study, cat-repellent (lime essential oil) and cat-attractant (oil containing pheromone) active ingredients were successfully microencapsulated using eco-friendly physicochemical methods namely simple coacervation (utilizing gum arabic) and molecular inclusion (utilizing β-cyclodextrin) vand subsequently applied onto polyester-based upholstery fabrics via the padding method.

Characterization analyses revealed that the choice of shell material and core material significantly alters particle size distribution and fiber-surface interactions:

Homogenity and Size Control: The molecular inclusion complex prepared with **β-cyclodextrin and Oil Containing Pheromone** exhibited the most narrow, stable, and homogeneous particle size distribution (mean size of 15.40 µm) among all formulations. Conversely, formulations containing lime oil tended to form broader, bimodal, or heterogeneous distributions with notable agglomerations.

Surface Morphology: SEM evaluations showed that while β-cyclodextrin complexes favor localized particulate adhesion and deep penetration into fiber crevices, the gum arabic matrix forms a more continuous, sheath-like film layer encapsulating the polyester fibers. Notably, the gum arabic/lime oil combination yielded widespread nano-scale spherical clusters, which drastically increase the active surface area.

These structural differences are expected to directly govern the release kinetics and longevity of the functional scents. While film-forming structures (gum arabic) may provide long-term controlled release, highly integrated nanometer/micrometer particulate formations β-cyclodextrin) could ensure durability against physical wear.

Consequently, the core-shell architectures optimized in this laboratory phase have established a solid foundation for functional upholstery fabrics designed to manage pet behavior. The actual behavioral efficacy of these developed fabrics, the exact breakdown of the active components (to be fully evaluated via GC-MS), and the long-term scratching preferences of domestic cats will be conclusively determined in the subsequent field study phase.

ACKNOWLEDGMENTS
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THE EFFECT OF DART GEOMETRY ON DYNAMIC FIT PERFORMANCE IN CIRCULAR KNITTED FABRICS

Scientific paper
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ABSTRACT: *This study is a research paper aiming to investigate the fit performance of different dart manipulation techniques in garments made from circular knitted fabrics under dynamic body movements. In this research designed in an experimental pattern with a control group, three different dart manipulation techniques (shifting to the shoulder, to front centre, and to side seam) were applied to four different circular knitted fabrics (jacquard interlock, ottoman, three-thread fleece, and rib knit) and a woven fabric as a control group. The samples were evaluated using visual analysis during four basic arm movements (abduction, elevation, flexion, extension). The findings demonstrated that, owing to the inherent elasticity of knitted fabrics, the displacement at the dart apex was lower than that observed in woven fabrics (+1 cm versus +3 cm), and no sensation of tightness was reported for any of the knitted fabric samples. These findings suggest that the influence of dart geometry cannot be considered independently of fabric type, as the two factors jointly affected garment performance. In particular, the centre-front shifted dart technique (P2) provided an excellent fit in rib-knit fabric without causing any surface distortion. In contrast, the side-seam shifted dart technique (P3) resulted in pronounced armhole wrinkles in some fabric types. Findings emphasize the importance of selecting the appropriate fabric–dart combination to optimize dynamic comfort and garment aesthetics, while providing practical guidance for dart design in ready-to-wear knitted garments.*

Keywords: *Circular knitted fabric, dart manipulation, dynamic fit, garment comfort.*

UTICAJ GEOMETRIJE UŠIVAKA NA DINAMIČKE KARAKTERISTIKE PRISTAJANJA KOD KRUŽNO PLETENIH MATERIJALA

APSTRAKT: *Ova studija predstavlja istraživački rad čiji je cilj ispitivanje performansi pristajanja različitih tehnika premeštanja ušitaka (dart manipulation) u odevnim predmetima izrađenim od kružno pletenih tkanina tokom dinamičkih pokreta tela.*

Istraživanje je sprovedeno prema eksperimentalnom dizajnu sa kontrolnom grupom. Tri različite tehnike premeštanja ušitaka (premeštanje ka ramenu, prednjem središtu i bočnom šavu) primenjene su na četiri različite kružno pletene tkanine (žakard interlok, otomanski plet, troslojni flis i rebrasti plet), dok je tkana tkanina korišćena kao kontrolna grupa. Uzorci su procenjivani metodom vizuelne analize tokom četiri osnovna pokreta ruke (abdukcija, elevacija, fleksija i ekstenzija). Rezultati su pokazali da je, zahvaljujući prirodnoj elastičnosti pletenih tkanina, pomeranje u vrhu ušitka bilo manje nego kod tkanih materijala (+1 cm naspram +3 cm), pri čemu ni kod jednog uzorka od pletenih tkanina nije zabeležen osećaj zatezanja. Dobijeni rezultati ukazuju da se uticaj geometrije ušitka ne može posmatrati nezavisno od vrste materijala, jer ova dva faktora zajednički utiču na performanse odevnog predmeta. Posebno se pokazalo da je tehnika premeštanja ušitka ka prednjem središtu (P2) obezbedila odlično pristajanje kod rebrastog pleta bez pojave deformacija na površini materijala. Nasuprot tome, tehnika premeštanja ušitka ka bočnom šavu (P3) dovela je do izraženih nabora oko rukavnog otvora kod pojedinih vrsta materijala. Rezultati naglašavaju značaj pravilnog izbora kombinacije materijala i tehnike ušitka radi optimizacije dinamičke udobnosti i estetskog kvaliteta odeće, uz pružanje praktičnih smernica za projektovanje ušitaka u konfekcijskoj proizvodnji odevnih predmeta od pletenih materijala.

Ključne reči: *Kružno pleteno platno, premeštanje ušitaka, dinamičko pristajanje, udobnost odeće.*

1. INTRODUCTION

Textiles primarily include woven and knitted fabrics. Knitted fabrics are formed by interlocking yarn loops, providing high flexibility and extensibility [1]. Among weft-knitted structures, circular knitted fabrics are widely used in apparel because their elasticity enables garments to conform more closely to body dimensions and movement than woven fabrics. Garment performance should be evaluated not only through fabric mechanics but also through anthropometric and ergonomic principles, which support garment fit, comfort, and functionality during movement [2–4]. Garment comfort results from the interaction of fabric properties, pattern design, garment fit, and body movement. Clothing must not only protect the wearer from environmental conditions [5] but also accommodate different body morphologies and postures [6]. Although body type, shape, and posture influence garment fit, the present study employed a standard women’s size 40 body to eliminate body-shape variability and evaluate the effects of fabric type and dart manipulation. Because body dimensions change continuously during movement, garments must adapt to these changes to maintain comfort and freedom of movement [7]. Previous research has mainly examined the physical, comfort, and functional properties of knitted fabrics, including the effects of fibre composition, spinning technology, sewing, and manufacturing parameters [8]–[10]. However, limited attention has been given to the interaction between knitted fabric structure and dart manipulation under dynamic conditions. This study addresses this gap by investigating the combined effects of three dart manipulation techniques (KP1, KP2,

and KP3) and four circular knitted fabric types—jacquard interlock, ottoman, three-thread fleece, and rib knit—on garment fit during body movement. A post-test experimental design was adopted, using woven-fabric garments as the control group and circular knitted garments as the experimental groups. Accordingly, this study seeks to answer the following questions:

1. How do different dart manipulation techniques applied to various circular knitted fabrics influence neckline shape and bust dart behaviour during dynamic arm movements compared with woven control samples?
2. How do dart manipulation techniques affect the armhole, side seam, and overall garment silhouette during dynamic movements?
3. How do different dart geometries influence surface deformation characteristics, including folds, ripples, and wrinkles, in circular knitted garments under dynamic body postures?

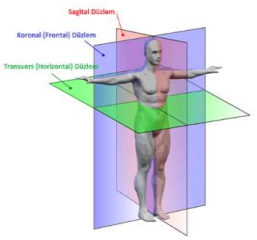
2. DART MANIPULATION IN GARMENT SHAPING

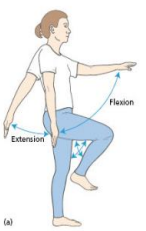
Dart manipulation is a fundamental patternmaking technique that influences garment fit, three-dimensional shaping, and freedom of movement. By transferring, rotating, relocating, or eliminating darts, different silhouettes can be achieved while preserving garment fit. Although widely applied to woven fabrics, its behaviour in circular knitted fabrics remains insufficiently understood because the elasticity and recovery of knitted structures modify the performance of conventional dart constructions during movement. Garment performance depends on the continuous interaction between the human body, clothing, and the environment [11]. Accordingly, accurate patternmaking is required to transform three-dimensional body geometry into two-dimensional garment patterns while accommodating body shape and movement [12, 13]. Standardized anthropometric measurement systems support accurate sizing and pattern development [14, 15]. Among these, the Müller and Sohn system is widely recognized for its anatomical accuracy and was therefore used to develop all garment patterns in this study [16, 17]. In women's bodice patternmaking, the bust dart is a principal shaping element that controls garment fit [18].
Dart manipulation involves relocating or rotating darts while maintaining garment volume and fit, thereby enabling alternative design solutions without altering the basic garment structure [19]. A dart is a triangular wedge that removes excess fabric to transform a flat textile surface into a three-dimensional form conforming to the human body, particularly around curved regions such as the bust, waist, and hips [20–22]. Structurally, it consists of a dart point, dart legs, and a dart intake, which together determine the degree of shaping achieved [23, 24]. Depending on design requirements, darts may be transferred using slash-and-spread or pivot techniques [19]. Among the various dart types reported in the literature, including French and double-pointed darts [22–24], the straight dart is the most widely used for shaping bodices, skirts, and trousers. Proper construction and sewing are essential for achieving the intended fit and appearance [22, 23]. Because it is the most common bust-shaping method in apparel patternmaking, the present study focuses exclusively on the straight bust dart, to which three different dart manipulation techniques were applied.

3. ANATOMICAL BASIS OF DYNAMIC ARM MOVEMENTS IN GARMENTS

Darts, which provide garments with three-dimensional shaping, are subjected to varying mechanical stresses during body movement. Understanding the interaction between dart geometry, fabric structure, and these stresses requires consideration of the fundamental arm movements used in dynamic garment evaluation.

Body movement continuously deforms garments during daily activities, making ergonomic garment design dependent on three-dimensional conformity with the human body while allowing unrestricted movement [25, 27]. Accordingly, garments should accommodate body shape and provide sufficient ease for everyday activities [28, 29]. Owing to their elasticity, flexibility, and wrinkle resistance, knitted fabrics are particularly suitable for achieving dynamic comfort [30]. Incorporating dynamic anthropometric data into garment design further improves wear performance by accommodating coordinated body movements [31]. Human movements occur around joints within the sagittal, frontal (coronal), and transverse anatomical planes [25, 26]. Because the shoulder is the primary reference joint for upper-limb motion, this study evaluates movements performed in the sagittal and frontal planes. Flexion and extension occur in the sagittal plane, whereas abduction and elevation occur in the frontal plane (Figure 1). Flexion decreases the angle between body segments, whereas extension increases it by returning the joint toward its anatomical position [33–35]. Abduction is the lateral movement of the arm away from the body's midline in the frontal plane [25, 26, 33, 34], while elevation refers to raising the arm above shoulder level [25, 33, 34] (Figures 2 and 3).





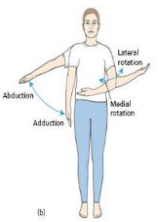


Figure 1 (left): Anatomical planes and axes of the human body [32]
Figure 2 (middle): Flexion and extension movements [26]
Figure 3 (right): Abduction movement [26]

4. EXPERIMENTAL

4.1. Materials

In this study, the control samples were constructed from plain-woven cotton sheeting fabric, whereas the experimental samples were produced using four different knitted fabrics. The control fabric was a finished, firm-handle cotton fabric with a mass per unit area of 138 g/m², a fabric cover factor of 24 × 18 (24 ends/cm and 18 picks/cm) and was woven from Ne 18/1 warp and Ne 20/1 weft 100% cotton yarns. The fabric mass per unit

area was determined in accordance with TSE 251, the warp and weft densities were measured according to TSE 250 EN 1049-2, and the warp and weft yarn lengths were calculated following TSE 254. For the experimental phase of the study, double-knit fabrics were selected based on their suitability for industrial garment manufacturing. The selected fabrics exhibited minimal extension during marker spreading, could be sewn easily on industrial sewing machines, possessed high dimensional stability and structural integrity without excessive stiffness, and had a medium fabric weight. Accordingly, jacquard interlock, Ottoman, three-thread fleece, and rib knit fabrics with a greige fabric weight of 250 g/m² or higher were used (Figure 4).

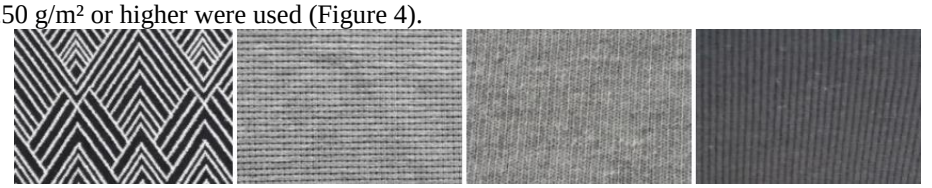


Figure 4 (from left to right): Knitted fabrics used in the study: (a) jacquard interlock, (b) Ottoman, (c) three-thread fleece, and (d) rib knit (Arslan, 2021)

The jacquard interlock fabric had a mass per unit area of 340 g/m² and a greige width of 150 cm. It was knitted using 70-denier polyamide 6.6 covered yarn with a 40-denier elastane core (70/40), Ne 28/1 polyester–viscose (65/35) black yarn, and Ne 30/1 white cotton yarn. The Ottoman fabric had a mass per unit area of 250 g/m² and a greige width of 155 cm. Its composition consisted of 70-denier polyamide 6.6 covered yarn with a 40-denier elastane core (70/40), Ne 28/1 cotton–polyester (50/50) grey yarn, and 150D/48F white polyester filament yarn. The three-thread fleece fabric had a mass per unit area of 265 g/m² and a greige width of 180 cm. It was knitted from Ne 30/1 cotton–polyester (50/50) grey mélange yarn and Ne 20/1 100% carded cotton yarn. The rib knit fabric had a mass per unit area of 280 g/m² and a greige width of 144 cm. It was knitted from Ne 30/1 cotton–polyester (50/50) black yarn.

4.2. Methods

An experimental comparative study with a control group was conducted to investigate the effects of dart manipulation techniques on the dynamic fit of circular knitted garments. Three control garments were produced from woven fabric using three dart manipulation techniques, while twelve experimental garments were prepared by applying the same techniques to four circular knitted fabric types. All samples were developed under standardized conditions and marked with temporary reference lines to facilitate visual evaluation. Each garment was fitted to a standardized mannequin and photographed during four fundamental arm movements: abduction, elevation, flexion, and extension. Dynamic garment performance was assessed through visual analysis of neckline shape, dart behaviour, armhole fit, side-seam alignment, fabric tension, garment conformity, and surface deformations such as folds, waviness, and wrinkles. Observations were recorded using standardized evaluation forms and compared across fabric types and dart manipulation techniques.

4.3. Model Selection and Body Measurements

A healthy female model whose body measurements closely matched the Müller Patternmaking System (size 40) was selected for garment evaluation. Since size 40 represents the average body size of Turkish women, it was adopted as the reference size, and other size groups were excluded from the study. The research focused exclusively on the effects of dart manipulation techniques; therefore, body morphology was controlled by using a single model throughout the experiments. Body measurements required for pattern development were obtained directly from the model using standard anthropometric measurement procedures while maintaining a natural standing posture. All garment samples were developed according to these measurements (Table1). Based on the anthropometric assessment, the model exhibited an apple-shaped endo-ectomorphic body type, characterized by greater fat distribution in the upper body than in the lower body.

4.4. Preparation of the Control and Experimental Samples

The bust darts, shoulder seams, and side seams were sewn with a 2.5 mm stitch length, while standard presser foot pressure and thread tension settings were maintained throughout. To ensure consistency, the knitted fabric samples were produced using the same machine settings and construction procedures, and no non-extensible tape or fusible interfacing was applied to the bust darts. Based on the model's body measurements, a basic bodice pattern was developed according to the Müller Patternmaking System, after which three dart manipulation techniques were applied to generate the experimental pattern variants (Figure 5).

Table 1: Comparison of the standard body measurements of the Müller Patternmaking System (Size 40) and the model's body measurements.

Müller Patternmaking System (Size 40 Standard Women's Body Measurements)		Model's Measurements	
Height	164	Height	161
Bust Circumference	100	Bust Circumference	96
Waist Circumference	76	Waist Circumference	79
Hip Circumference	106	Hip Circumference	104
Sleeve Length	59	Sleeve Length	61

Figure 5: Appearance of the basic bodice, constructed according to the model's body measurements, on the model (Arslan, 2021).

5. RESULTS

This section presents the dynamic fit performance of three dart manipulation techniques (P1: shoulder transfer, P2: centre-front transfer, and P3: side-seam transfer) applied to four circular knitted fabrics and a woven control fabric during four upper-limb movements. The findings are organized according to the research objectives, with detailed visual evaluation results presented in Tables 2–4.

5.1. Findings for Dart Manipulation Technique 1 (Shoulder Transfer)

No neckline deformation was observed in either the woven control or knitted fabric samples during any of the evaluated arm movements (Table 2). The behaviour of the bust dart apex varied according to fabric type. The woven control sample exhibited a **3 cm** upward displacement during all movements, whereas the displacement was limited to **1 cm** in the jacquard interlock, Ottoman, and three-thread fleece fabrics, and **0.5 cm** in the rib knit fabric. Although minor folds developed around the dart during movement, dart geometry remained stable. The reduced displacement observed in the knitted fabrics indicates that their inherent elasticity better accommodated body movement, with the rib knit showing the best performance. The woven control sample exhibited noticeable tension around the armhole, side seam, and body reference line during most movements, with the greatest discomfort reported during extension. In contrast, none of the knitted fabrics showed perceptible tension, regardless of differences in fabric structure or mass (250–340 g/m²). Surface analysis showed pronounced folds in the woven control sample throughout all movements. The knitted fabrics generally exhibited fewer and less severe surface deformations, with the rib knit displaying the least visible folds because its rib structure effectively concealed surface irregularities (Table 3).

5.2. Findings for Dart Manipulation Technique 2 (Centre-Front Transfer)

No neckline deformation was observed in either the woven control or knitted fabric samples during any of the evaluated arm movements (Table 4). The displacement of the bust dart apex varied according to fabric type. The woven control sample exhibited a 2.5 cm upward displacement during all movements, whereas the knitted fabrics showed a maximum displacement of 1 cm. No displacement occurred in the jacquard interlock fabric during extension, while the three-thread fleece fabric developed localized depressions around the dart. Nevertheless, dart geometry remained stable in all samples. Compared with the woven control, the reduced dart displacement in the knitted fabrics demonstrates their superior ability to accommodate body movement through their elastic loop structure. The woven control sample exhibited slight tension around the armhole and side seam, particularly during extension and frontal-plane movements. In contrast, none of the knitted fabrics showed perceptible tension at the armhole, side seam, or body reference line, regardless of differences in fabric structure or mass. Surface evaluation revealed slight to moderate folds in the woven control and most knitted fabrics, with fold severity varying according to fabric type and movement. Jacquard interlock, Ottoman, and three-thread fleece fabrics exhibited longitudinal folds, particularly during elevation and flexion. In contrast, the rib knit fabric showed no visible surface deformation during any arm movement, indicating that Dart Manipulation Technique 2 (centre-front transfer) provided the most compatible and visually stable solution for this fabric type (Table 5).

5.3. Findings for Dart Manipulation Technique 3 (Side-Seam Transfer)

Examination of the neckline in Dart Manipulation Technique 3 (P3) revealed no neckline deformation in either the woven control sample or any of the knitted fabrics during upper-limb movements (Table 6). Differences were observed in the displacement of the bust dart

apex. In the woven control sample, the dart apex shifted 3 cm upward toward the neckline during both frontal- and sagittal-plane movements, accompanied by pronounced folds around the dart while the overall dart geometry remained stable. Additional shoulder-directed folds appeared during abduction and extension and became more pronounced, extending toward the armhole, during elevation and flexion. In contrast, all knitted fabrics exhibited only a 1 cm upward displacement of the dart apex, with no deformation of the dart geometry. Evaluation of the armhole, side seam, and body reference line showed that the woven control sample exhibited tension along the side seam and body reference line, whereas no perceptible tension occurred in the knitted fabrics. Variations in knit structure and fabric mass (250–340 g/m²) did not influence tension behaviour. Surface appearance analysis revealed slight folds in the woven control sample during abduction and extension and more pronounced folds during elevation and flexion. The jacquard interlock fabric showed minor folds during abduction and extension but developed deep pleat-like folds toward the armhole during elevation and flexion. The Ottoman and three-thread fleece fabrics exhibited deep folds around the shoulder, armhole, and bust dart during most movements, although only slight folds occurred during extension in the three-thread fleece fabric. The rib knit fabric showed pronounced folds during frontal-plane movements, slight folds during flexion, and no visible folds during extension. These findings indicate that Dart Manipulation Technique 3 (side-seam transfer) was particularly compatible with the rib knit fabric during extension (Table 7).

Table 2: Appearance of the samples prepared using dart manipulation technique 1 during upper-limb movements

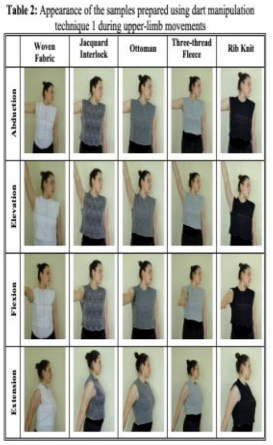


Table 3: Dynamic fit performance of dart manipulation technique 1 (shoulder transfer)

Evaluation Criterion	Control (Woven)	Jacquard Interlock	Ottoman	Three-thread Fleece	Rib Knit
Neckline deformation	None	None	None	None	None
Bust dart apex displacement	+3 cm	+1 cm	+1 cm	+1 cm	+0,5 cm
Dart geometry	Maintained	Maintained	Maintained	Maintained	Maintained
Perceived tension	Present	Absent	Absent	Absent	Absent
Surface folding	Pronounced	Very slight	Dependent on movement type	Dependent on movement type	Dependent on movement type

Table 4: Appearance of the samples prepared using dart manipulation technique 2 during upper-limb movements

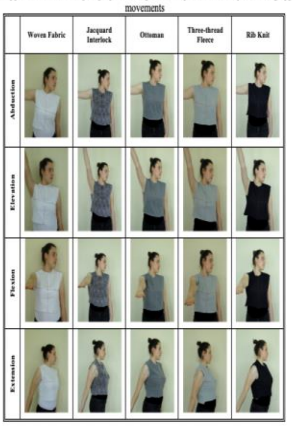


Table 5: Dynamic fit performance of dart manipulation technique 2 (centre-front transfer)

Evaluation Criterion	Control (Woven)	Jacquard Interlock	Ottoman	Three-thread Fleece	Rib Knit
Neckline deformation	None	None	None	None	None
Bust dart apex displacement	+2.5 cm	+1 cm*	+1 cm	+1 cm	+1 cm
Dart geometry	Maintained	Maintained Stable during extension	Maintained	Maintained **collapse of the bulge**	Maintained
Perceived tension	Very slight	Absent	Absent	Absent	Absent
Surface folding	Dependent on movement type	Dependent on movement type	Present in all movement types	Dependent on movement type	Absent

Table 6: Appearance of the samples prepared using dart manipulation technique 3 during upper-limb movements

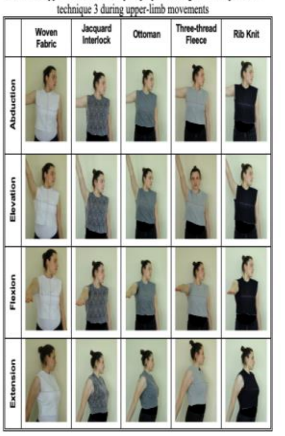


Table 7. Dynamic fit performance of dart manipulation technique 3 (Side-seam transfer)

Evaluation Criterion	Control (Woven)	Jacquard Interlock	Ottoman	Three-thread Fleece	Rib Knit
Neckline deformation	None	None	None	None	None
Bust dart apex displacement	**+3 cm**	+1 cm	+1 cm	+1 cm	+1 cm
Dart geometry	Maintained	Maintained	Maintained	Maintained	Maintained
Perceived tension	Very slight	Absent	Absent	Absent	Absent
Surface folding	Dependent on movement type	Dependent on movement type	Dependent on movement type	Dependent on movement type	Dependent on movement type

6. CONCLUSION

This study investigated the effects of three dart manipulation techniques on the dynamic fit performance of garments produced from four circular knitted fabrics and one woven control fabric. Garment performance was qualitatively evaluated during abduction, elevation, flexion, and extension. The neckline remained stable regardless of fabric type, dart manipulation technique, or movement. In contrast, the woven control fabric exhibited considerably greater dart apex displacement (+2.5–3 cm) than the knitted fabrics, where displacement was generally limited to +1 cm. The rib knit showed the best dynamic conformity under Technique P1 (+0.5 cm), while localized depressions in the three-thread fleece under Technique P2 indicated that fabric bulk also affected deformation.
Noticeable tension occurred only in the woven control sample, whereas none of the knitted fabrics exhibited perceptible tension under any dart manipulation technique, demonstrating the superior dynamic comfort provided by their structural elasticity.
Surface deformation depended on the interaction between dart manipulation technique and fabric type. The centre-front transfer (P2) produced the best performance in the rib knit, with no visible deformation, whereas the Ottoman fabric developed pronounced folds under the same technique. The side-seam transfer (P3) generated deep armhole folds in the jacquard interlock and three-thread fleece fabrics, indicating reduced aesthetic performance. Overall, the centre-front transfer (P2) is recommended for rib knit fabrics, the shoulder transfer (P1) appears suitable for smoother knitted structures, and the side-seam transfer (P3) should be used cautiously because of its tendency to create armhole folds. Future research should incorporate quantitative evaluation methods, larger participant groups, and additional dart types to further improve understanding of dynamic garment fit.

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SESSION II
DESIGN

DESIGN AND DEVELOPMENT OF SUSTAINABLE ADAPTIVE CLOTHING COLLECTIONS

Review paper
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ABSTRACT: *Adaptive clothing development encompasses the design, innovation, and functionality of outfits created for individuals with different abilities. This field has evolved in response to changing societal perceptions of users' needs, technological advancements, and historical developments that have shaped the rights and inclusion of people with disabilities. Adaptive clothing plays a crucial role in enhancing quality of life by offering functional and aesthetically considered solutions that address diverse physical and cognitive challenges, thereby supporting greater inclusivity within the fashion industry. Contemporary adaptive clothing increasingly integrates advanced technologies and inclusive design principles to improve usability, accessibility, independence, and dignity. Despite significant progress, challenges persist, particularly the higher costs associated with adaptive clothing, which may limit access for those most in need. In this context, sustainable adaptive textiles represent a promising intersection of environmental responsibility and functional design. The paper outlines major historical shifts in the social understanding of bodily diversity, from early cultural and religious frameworks through industrialisation, the development of welfare systems, and the disability rights movement, to contemporary perspectives. Particular emphasis is placed on the role of textiles, clothing, and material culture in shaping and reflecting societal attitudes. The study also critically examines sustainability in adaptive textiles and clothing, including accessories and footwear, highlighting the growing social and economic importance of this market segment. Sustainability is analysed from material-based, process-related, and design-oriented perspectives. The paper concludes by identifying key challenges in designing sustainable adaptive clothing collections and outlining directions for future research and development.*

Keywords: *adaptive clothing, fashion, sustainability, inclusive design, universal design.*

DIZAJN I RAZVOJ ODRŽIVIH KOLEKCIJA ADAPTIVNE ODEĆE

APSTRAKT: *Razvoj adaptivne odeće obuhvata dizajn, inovacije i funkcionalnost odevnih predmeta namenjenih osobama sa različitim sposobnostima. Ova oblast se razvijala kao*

odgovor na promene u društvenom razumevanju potreba korisnika, tehnološki napredak i istorijske procese koji su oblikovali prava i inkluziju osoba sa invaliditetom. Adaptivna odeća ima značajnu ulogu u unapređenju kvaliteta života korisnika, jer pruža funkcionalna i estetski promišljena rešenja za različite fizičke i kognitivne izazove, čime doprinosi većoj inkluzivnosti u modnoj industriji. Savremena adaptivna odeća sve više integriše napredne tehnologije i principe inkluzivnog dizajna radi poboljšanja upotrebljivosti, pristupačnosti, samostalnosti i dostojanstva korisnika. Uprkos značajnom napretku, i dalje postoje izazovi, naročito viši troškovi povezani sa adaptivnom odećom, koji mogu ograničiti pristup onima kojima je ona najpotrebnija. U tom kontekstu, održivi adaptivni tekstili predstavljaju obećavajuću sintezu ekološke odgovornosti i funkcionalnog dizajna. Rad prikazuje glavne istorijske promene u društvenom razumevanju telesne raznolikosti, od ranih kulturnih i religijskih okvira, preko industrijalizacije, razvoja sistema socijalne zaštite i pokreta za prava osoba sa invaliditetom, do savremenih perspektiva. Poseban akcenat stavljen je na ulogu tekstila, odeće i materijalne kulture u oblikovanju i odražavanju društvenih stavova. Pored toga, studija kritički razmatra aspekte održivosti adaptivnih tekstila i odeće, uključujući modne dodatke i obuću, ističući rastući društveni i ekonomski značaj ovog tržišnog segmenta. Održivost se analizira iz materijalne, procesne i dizajnerske perspektive. Rad se završava identifikacijom ključnih izazova u dizajniranju održivih adaptivnih kolekcija odeće i ukazivanjem na smernice za buduća istraživanja i razvoj.

Ključne reči: *adaptivna odeća, moda, održivost, inkluzivni dizajn, univerzalni dizajn.*

1. INTRODUCTION

Adaptive clothing refers to garments specifically designed or modified to meet the needs of individuals with physical disabilities, older adults, the infirm, post-operative patients, and those with arthritis, quadriplegia, or paraplegia. Difficulties may result from an inability to manipulate fastenings or from a limited range of motion needed for independent dressing. Adaptive clothing also makes dressing and undressing easier for caregivers, nurses, and hospital staff, while providing non-restrictive comfort for the wearer. Furthermore, it enables individuals with disabilities and older adults to maintain dignity, exercise some independence in self-care, benefit from improved access to medical devices and care products, both for themselves and for attending healthcare professionals [1].
The global adaptive clothing market was valued at approximately €17.51 billion in 2025. It is projected to grow from €18.93 billion in 2026 to around €30.31 billion by 2034, reflecting a compound annual growth rate (CAGR) of 6.06% over the forecast period. This indicates a steady increase in demand for adaptive clothing, driven by demographic trends, rising awareness of inclusive fashion, and ongoing innovation in textile and clothing products. Adaptive clothing design and development are being driven by growing demand for clothing with specialised, personalised features that match wearers' mobility levels, medical conditions, body types, sizes, and ages. Advances in digital design tools, online platforms, and flexible manufacturing concepts are making personalised adaptive clothing

more accessible, supporting global market growth. In addition, expanding partnerships between manufacturers and retailers and hospitals, rehabilitation centres, and residential care facilities, which require significant use of adaptive products for assisted living, are creating new market opportunities. Ongoing recommendations from healthcare professionals on the use of adaptive clothing to support patients with mobility challenges are also expected to further stimulate product demand [2].

2. HISTORY OF ADAPTIVE CLOTHING

2.1. Attitudes towards disability

Throughout history, perceptions of disability have varied across cultures and periods, with most viewing physical differences as inferior. In ancient Greece and Rome, people with disabilities and physical impairments were often looked down upon and stigmatised. Conversely, some societies regarded disabled individuals as possessing spiritual insight. In certain Indigenous traditions, disabled individuals were considered gifted with unique wisdom, serving as healers, shamans, or storytellers. This reverence often meant that disabled people were integrated into society rather than excluded [3, 4]. During the Middle Ages, many physical and mental health conditions were believed to be caused by demons or explained through religious beliefs about divine intervention. With the Enlightenment of the 17th and 18th centuries, physical and mental impairments came to be understood as having underlying biological causes, some of which could be treated with medical intervention. In the 18th century, families of individuals with disabilities were mainly responsible for their care, while the church was the primary provider of charitable care outside the family [3, 5].

The rise of industrialisation in the 18th and 19th centuries marked a significant turning point in attitudes towards disability. The ability to work in labour-intensive environments became a key measure of value. Disabled individuals were classified as “unfit” for work and excluded from society. At the same time, the institutionalisation of disabled individuals took place, further entrenching harmful stereotypes and beliefs. Asylums were built in remote areas, far from amenities, services, and families. The location of these “places of safety and refuge” made it virtually impossible for families to visit and kept the residents hidden from view. Alongside this concealment, the Victorian era introduced so-called “freak shows”, which involved gathering people with disabilities and abnormalities to be displayed for public viewing. In this way, people with disabilities were portrayed as outsiders, different from the rest of society [3].

In the late 20th century, organised disability rights movements led to legislative milestones such as the Americans with Disabilities Act (ADA), which aimed to dismantle barriers to inclusion and accessibility. Contemporary attitudes increasingly recognise disability as an aspect of human diversity. Despite significant progress, challenges in accepting different abilities persist, including the continuing need for broader societal acceptance and better representation in fashion [6].

Major historical events, particularly wars and economic shifts, have significantly influenced how societies address disability. The number of disabled individuals in society increased sharply, prompting governments to act. Welfare systems were established with

an emphasis on rehabilitation, marking a major shift towards recognising the potential contributions of disabled individuals. Some of the earliest disability welfare systems emerged in ancient China and the Roman Empire to support war veterans. The two World Wars had a particularly profound effect on disability inclusion. Western countries experienced a rise in disabled veterans who demanded improved medical care, employment opportunities and accessibility. These demands helped establish the basis for modern disability policies, including rehabilitation programmes and public accessibility initiatives [4].

2.2. Disability models

The medical model defines disability as a personal characteristic resulting from disease, trauma, or other health conditions, which must be addressed individually by identifying the causes and cures of the impairment or by finding ways to adjust or change behaviour to enable full participation in society. In this model, medical care is considered the primary means of managing disability. Disability is viewed as a defect that medicine and healthcare professionals are expected to fix. This perspective contributes to the stigmatisation, impoverishment, and institutionalisation of disabled individuals [7, 8].

Later, Oliver introduced the social model of disability, based on his belief that individual limitations are not the cause of the problem. Rather, the problem lies in society's failure to provide appropriate services and to ensure that the needs of disabled people are adequately considered in social organisation. This model was developed mainly by individuals previously labelled as disabled under the medical model of disability, who sought greater opportunities for self-advocacy and autonomy [8].

More recently, disability theory has developed into contemporary critical disability theory, a diverse and interdisciplinary set of theoretical approaches. Critical disability theory analyses disability as a cultural, historical, relational, social and political phenomenon, and presents disability as a methodology applicable to various subjects and phenomena [9, 10].

Figure 1: The development of disability models over time

The transition from the medical to the social, and then to the critical model of disability, shows how disability is understood and how these understandings significantly shape legislation and the development of disability rights. Today, attitudes towards disability remain influenced by historical legacies, yet there is growing recognition of the importance of inclusion and representation. Although challenges persist, the evolution of societal perceptions reflects a gradual shift towards understanding disability as an aspect of human

diversity rather than merely a limitation. This shift is also evident in the development of adaptive clothing, which seeks to meet the needs of individuals with disabilities while promoting dignity and style in personal expression.

2.3. Historical development of adaptive clothing

The evolution of adaptive clothing has been significantly influenced by societal perceptions of disability, advances in textile and clothing technology, and key historical events. Throughout history, adaptive clothing has developed from individualised, necessity-driven solutions into an increasingly recognised field of inclusive design and fashion.

Although the term “adaptive clothing” is relatively new, the practice itself dates back to ancient times. In ancient Egypt and Rome, garments were often modified to accommodate bodily differences, with tunics and togas altered to facilitate mobility and comfort for individuals with impairments [11].

Initially, clothing was tailored to individual needs and often produced collaboratively by wearers and local seamstresses, ensuring functionality alongside cultural and aesthetic considerations. With the industrial revolution, mass manufacturing took precedence, leading to a neglect of inclusive clothing for people with disabilities [12]. In the 19th century, for example, corsets were modified to accommodate women with physical disabilities. These adaptations allowed greater flexibility and ease of movement, ensuring that women with disabilities could still enjoy fashionable clothing without sacrificing comfort. In the late 19th and early 20th centuries, technological innovations began to shape adaptive design, such as the invention of the modern snap (1885), the zipper (1893) and Velcro (1940s). Fastening was simplified, while later developments further enhanced accessibility for individuals with limited dexterity. Despite these advances, adaptive clothing remained largely functional and was frequently associated with medical or institutional contexts rather than fashion [12, 13].

A major shift occurred in the mid-20th century, particularly following WWII. The return of injured veterans increased awareness of the practical challenges faced by disabled individuals, leading to the development of garments designed to support independence. From the 1950s to the 1970s, designers such as Helen Cookman began integrating functionality with aesthetic value, producing collections that addressed both usability and style, although these efforts remained relatively marginal within the broader fashion industry [11–14].

In the late 20th century, adaptive clothing came to be recognised as a distinct category, with specialised brands emerging in the 1980s and the term “adaptive fashion” gaining wider usage. Nevertheless, many garments continued to reflect a “medicalised” aesthetic, prioritising practicality over personal expression [12, 14].

In the 21st century, adaptive clothing has undergone significant transformation, driven by technological innovation, disability activism, and an increasing emphasis on inclusion. Innovations such as magnetic closures, elasticated materials, temperature-regulating and sensory-friendly fabrics, 3D-printed accessories, and designs accommodating prosthetics or seated bodies have improved both functionality and independence. Contemporary adaptive fashion increasingly seeks to reconcile accessibility with style, challenging

historical exclusions and positioning clothing as a means of identity and social participation rather than merely a functional necessity [13, 14]. As the fashion industry continues to embrace inclusivity, the future of adaptive clothing looks promising. Designers are constantly pushing boundaries and finding new ways to create clothing that meets the diverse needs of individuals with disabilities [13].
Overall, the history of adaptive clothing demonstrates a transition from personalised adaptation, through industrial marginalisation, to a modern paradigm of inclusive design, reflecting broader shifts in the understanding of disability as a social, cultural, and physical phenomenon.

3. DESIGN AND DEVELOPMENT OF ADAPTIVE CLOTHING

The design and development of adaptive clothing, accessories, and footwear is a growing interdisciplinary field that brings together principles from fashion design, ergonomics, and healthcare. It focuses on creating garments that meet the specific functional, physical, and psychological needs of individuals with limited mobility, chronic conditions, or age-related impairments. Alongside functional requirements, designers also consider aesthetic value and personal expression, ensuring that functionality does not compromise style. Advances in materials science, textile machinery and processes, digital design technologies, and user-centred design approaches continue to shape the evolution of adaptive clothing, enabling more inclusive, customisable, and widely accessible solutions.

3.1. Benefits of adaptive clothing

Adaptive clothing provides many interconnected benefits for individuals with various challenges, including:

- **improved independence**: adapted styles, closures and fastenings enable quicker, less physically demanding dressing and undressing, giving wearers a sense of self-reliance and dignity [1, 15];
- **increased mobility**: clothing, footwear and accessories that incorporate or are compatible with mobility aids such as wheelchairs, walkers, or braces allow greater freedom of movement and reduce restrictions on daily activities [1];
- **reduced pain and discomfort:** the use of soft, comfortable materials, appropriate construction, labelling and closures helps prevent skin irritation, pain and discomfort associated with sensory sensitivities or medical conditions [1, 15];
- **customised fit**: a range of sizes and styles, including options for different body shapes and proportions, ensures a better fit and increased comfort for individuals with unique physical characteristics [1];
- **stylish, contemporary and discreet design options**: clothing, accessories, and footwear with unobtrusive adaptations meet diverse preferences, allowing individuals to express personal style while benefiting from functional features, thus enhancing confidence and promoting a positive body image [1, 15];
- **facilitated caregiving**: reduced time and effort required for dressing routines contribute to a more efficient and positive caregiving experience [1].

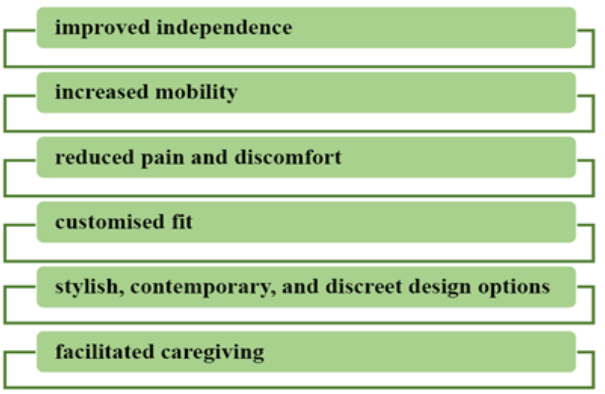

Figure 2: Key benefits of adaptive clothing

3.2. Characteristics and issues in the supply of adaptive clothing

Apart from the special features mentioned in previous chapters, the supply of adaptive clothing is characterised by a relatively limited product range, uneven market development, and varying availability across regions. Persistent issues remain regarding accessibility, affordability, and the extent to which products adequately meet the diverse needs of users. The most prominent characteristics and issues in the supply of adaptive clothing are as follows:

- The high price of adaptive clothing and similar products, due to production costs and small-scale or made-to-measure manufacture, limits demand among middle-income consumer groups worldwide [2].
- The absence of universally accepted design guidelines for adaptive clothing leads to inconsistencies among buyers regarding fit, comfort and functionality, which negatively impacts global product demand [2].
- There is a limited range of adaptive fashion products, and those that do exist often fail to express the personality of the people who need them or to meet all the needs of people with disabilities [16].
- Manufacturers of adaptive clothing and related products often lack knowledge about comfort, functionality and safety requirements and can be intimidated by the challenges of adaptive modifications [16].
- Online shopping, as an increasingly common way of buying textiles and clothing, often does not present adaptive clothing options and makes finding suitable clothing for people with disabilities very difficult [16].

3.3. Sustainability in adaptive clothing

As early as 1992, William McDonough & Partners formulated a set of sustainable design principles for the World Expo 2000. These later became known as “The Hannover Principles: Design for Sustainability”. The document is notable for its broad philosophical

and ethical scope and should be regarded as a living framework, committed to the ongoing transformation and deepening of our understanding of human interdependence with nature and with future generations [17, 18]. The principles are as follows:

- Insist on the right of humanity and nature to coexist in a healthy, supportive, diverse and sustainable condition.
- Recognise interdependence.
- Accept responsibility for the consequences of design decisions on human well-being, the viability of natural systems, and their right to coexist.
- Create safe objects of long-term value.
- Eliminate the concept of waste.
- Rely on natural energy flows.
- Understand the limitations of design.
- Seek constant improvement through the sharing of knowledge.
- Respect the relationships between spirit and matter [17, 18].

Product design and development play a fundamental role in the design and manufacture of sustainable products. The choices made during the product design and development process influence up to 80% of a product's environmental and social impacts. The selection of materials, forms, colours and production systems also affects the use and disposal of the product throughout its life-cycle, and the designer thus also influences sustainable consumption patterns [19]. This is also true for the design of adaptive clothing, footwear and accessories, which is a complex and interdisciplinary process involving a team of professionals with a wide range of expertise.

The adoption of sustainable materials is a key trend reshaping the global adaptive clothing market. Producers are increasingly prioritising environmentally friendly textiles, including organic cotton, recycled polyester, Tencel and hemp. This shift is driven by rising consumer demand for environmentally responsible products and by a broader industry transition towards circular economy principles. Manufacturers increasingly recognise that sustainable materials can reduce environmental impact, align with ethical consumer values and strengthen brand reputation. As a result, this trend is influencing both design and production processes, encouraging innovation in material, textile and clothing development as well as supply chain management. Greater emphasis is placed on durability, biodegradability and the responsible sourcing of raw materials, ensuring that adaptive garments are not only functional but also environmentally responsible. Ultimately, this approach is transforming production practices by embedding environmental awareness at every stage, from material selection through to the end of the product life-cycle [20]. Integrating sustainability principles into adaptive fashion is not merely an ethical consideration but a fundamental necessity:

- **Ethical sourcing and production**: Prioritising ethical labour practices and fair wages throughout the adaptive fashion supply chain is crucial to ensuring that the pursuit of inclusivity does not come at the expense of workers.
- **Environmentally responsible materials**: Using sustainable, eco-friendly materials in adaptive clothing production minimises environmental impact and aligns with

broader sustainability goals, including the use of recycled, upcycled and bio-based fabrics.

- **Circular economy models**: Adopting circular economy principles, such as garment recycling and take-back programmes, reduces waste and promotes resource efficiency within the adaptive fashion sector [20].

3.4. Examples of adaptive clothing collections and brands

As awareness grew, specialised adaptive clothing designers and brands emerged, recognising the diverse needs of the disabled community. They began creating stylish yet functional garments, paving the way for more inclusive fashion. Adaptive fashion became a symbol of empowerment, allowing individuals to dress with independence and confidence [14].

The mistaken belief that there is no history of clothing design for disabled users has had a number of repercussions. Not only is there a long history of clothing designed by and for disabled people, but in some cases it sets a higher standard than later efforts. Between 1955 and 1976, nearly thirty of the United States' top clothing designers created garments to fit disabled bodies under the Functional Fashions line. Brands ranged from high-end sportswear to everyday labels. Leading the charge was designer Helen Cookman, whose own disability was hearing loss, and who was one of the earliest pioneers of modern adaptive fashion. Helen Cookman and New York Times style editor Virginia Pope created functional, fashionable clothing to address the needs of disabled consumers in 1955. The garments included practical features such as side zippers, reinforced seams and crutch-friendly cuts to help disabled people dress independently. Cookman helped formalise adaptive design research in the mid-20th century and collaborated with major U.S. designers to develop items that were both fashionable and accessible. Together with Muriel E. Zimmerman, Cookman published an illustrated guide with information for disabled consumers and designers in 1961. However, after both she and Pope had died by 1978, adaptive fashion shifted away from its fashion emphasis towards functionality [21–23].

Vera Maxwell remained the longest collaborator, incorporating Functional Fashions elements into her garments for ten years. One of her best-known creations, the "Speed Suit", was designed for disabled bodies. With an elastane-knit top, it slipped over the head with no fastenings and was perfect for "the woman who wants to dress quickly" or "anyone whose fingers are crippled with arthritis". In 1963, Maxwell released the so-called "Rugby Suit", a tweed suit that included a matching lap robe for wheelchair users. It fastened with Velcro tape [21, 22, 24].

In 1975, the popular brand Levi's released an accessible pair of jeans that could be ordered by mail. The design was based on Cookman's patented "Trousers for a Handicapped Person", which featured zippers running the length of both legs and a belt that kept the front in place while the back unzipped for ease of use when going to the bathroom. Cookman died two years before this significant release [21, 23].

Contemporary designer Izzy Camilleri is widely recognised as a pioneer of stylish adaptive fashion. For several decades before founding her brand IZ Adaptive, Camilleri designed for a high-profile celebrity clientele. In 2004, after creating a bespoke garment for a

wheelchair user, she identified a significant gap in the market and the need to make well-designed, aesthetically appealing clothing accessible to a broader range of users. Established in 2009, IZ Adaptive has since been at the forefront of adaptive fashion, addressing the needs of individuals with diverse abilities. Camilleri's designs offer what may be described as "fashion freedom", combining comfort, ease of wear, and inclusivity without compromising on style. In September 2025, IZ Adaptive became part of the Silvert's family, a company that has been a leader in adaptive clothing since 1930 [25, 26].
Joe & Bella is a contemporary adaptive fashion brand founded in 2020 in Chicago, representing a significant shift within the industry towards inclusive, dignity-centred design for ageing and mobility-impaired populations. The company's conceptual foundation is rooted in the belief that functional clothing should not compromise personal identity, aesthetics or dignity. The brand emerged from a caregiving context, where the founders recognised that existing adaptive garments were often perceived as "ugly" or overly clinical, leading to resistance among older adults. The company emphasises three core principles: dignity and independence, the fusion of style and function, and a universal design philosophy. Joe & Bella not only addresses practical dressing challenges but also helps redefine how ageing and disability are represented within the fashion system [27, 28].
Despite some progress, the fashion industry has long struggled to achieve genuine inclusivity and accessibility, from runway representation to brand practices. Although companies such as Tommy Hilfiger, ASOS, Nike and Zalando have recognised the purchasing power of disabled consumers, they have often failed to meaningfully involve these users in the design processes intended to serve them. As a result, adaptive garments are frequently brought to market without adequate testing by their intended users, leading to shortcomings in functionality. In other cases, products promoted as accessible fail to reach the communities they are designed for [21, 22].

4. CHALLENGES IN THE DEVELOPMENT AND DESIGN OF ADAPTIVE CLOTHING

The design and development of adaptive clothing present a range of complex challenges that require careful consideration of both functional and aesthetic factors. Designers must balance practical concerns such as ease of dressing, accessibility, and compatibility with medical or mobility aids with the desire for visually appealing, contemporary, fashionable clothing. In addition, the diversity of user needs, including variations in age, gender, lifestyle, profession, physical ability, body shape, and medical conditions, makes standardisation difficult and often necessitates highly individualised solutions.
Further challenges arise from material selection, manufacturing constraints, and cost considerations, which can limit both accessibility and affordability. Ensuring that adaptive clothing remains inclusive and commercially viable, with potential for market growth, therefore requires ongoing innovation, interdisciplinary collaboration, and a user-centred design approach.
The key challenges in the development and design of adaptive clothing are as follows:

- **stigma**, which can only be overcome by positioning adaptive clothing and fashion as stylish, desirable and empowering;
- **limited accessibility** caused by users' lack of awareness of the existence and availability of adaptive clothing, insufficient visibility in mainstream retail environments, and limited marketing efforts by brands;
- **higher production costs** resulting from smaller production scales or made-to-measure manufacturing, specialised design features, and the use of special, high-performance, high-quality materials;
- **lack of standardised sizing and design across brands**, creating considerable challenges for consumers seeking well-fitting garments;
- **special safety measures required** due to the complexity of some types of adaptive clothing, footwear and accessories;
- **lack of standardised design principles**, leading to wide variation in essential features such as easy closures, accessible pockets and adaptive cuts, resulting in an inefficient and discouraging shopping experience for consumers of specialised apparel;
- **specialised knowledge and competencies required** to design adaptive products that meet specific needs, follow ergonomic principles and ensure both accessibility and sustainability;
- **inefficiencies in supply chains and distribution networks** that impede access for a wider customer base;
- **obstacles to implementing sustainable design principles** arising from the use of specific materials, material combinations and specialised components, the integration of complex manufacturing processes, elevated production and distribution costs, and the inherent challenges associated with recycling and upcycling [29, 1].

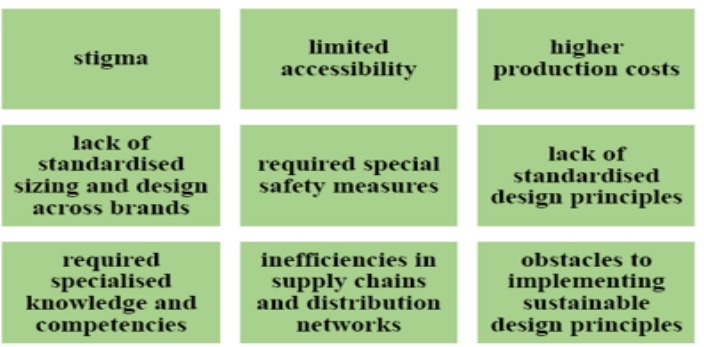

Figure 3: Key challenges in the development and design of adaptive clothing

5. CONCLUSION

The contemporary design, development and manufacture of adaptive clothing collections reflect broader societal shifts in the understanding of disability, moving from

marginalisation towards co-design, inclusion, diversity and user empowerment. Historical analysis shows that adaptive clothing has progressed from individualised, necessity-driven solutions to an increasingly recognised field of inclusive design, shaped by advances in technology and fashion, changes in social attitudes and the growing influence of disability rights movements and the media.

Today, adaptive clothing is a complex, interdisciplinary field that integrates principles of design, technology, ergonomics, healthcare, sustainability, quality and safety. Although the adaptive clothing market shows significant growth potential, it still faces persistent challenges, including high costs, limited availability, insufficient standardisation and a lack of meaningful user involvement in design processes. These challenges highlight the importance of adopting user-centred, participatory design approaches to ensure that products respond effectively to the diverse and specific needs of end users, including their emotional and aesthetic needs.

Furthermore, integrating sustainability principles into adaptive fashion is no longer optional but essential. It requires responsible material selection, ethical production practices, and the adoption of circular economy models. At the same time, achieving genuine inclusivity demands not only material and functional innovation but also cultural change within the fashion industry, including better representation and accessibility, and an end to disingenuous claims that a product is adaptive when, in fact, it is not and has been created solely to attract media attention and increase market share.

Critically, current approaches in the fashion industry often prioritise commercial opportunity over functional adequacy and social responsibility. As a result, products frequently fail to address users' lived experiences, reinforcing exclusion rather than reducing it. Addressing these issues requires a more rigorous policy framework that incorporates design standards, accessibility regulations and incentives for inclusive innovation.

Future progress in adaptive clothing and related products will depend on sustained interdisciplinary collaboration, technological innovation, and closer alignment between designers, manufacturers, healthcare professionals, and users. Only through such coordinated efforts can adaptive clothing fully realise its potential as both a functional necessity and a means of personal expression, contributing to a more inclusive and sustainable fashion system.

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DIGITAL FABRIC OF FASHION THROUGH THE INTEGRATION OF ENGINEERING AND DESIGN

Professional paper
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ABSTRACT: *The textile and apparel industry is currently experiencing a profound transformation driven by digitalization, sustainability concerns, and the rapid advancement of artificial intelligence technologies. Traditional design and manufacturing approaches are increasingly being replaced by digital systems that enable designers and engineers to develop, evaluate, and optimize products in virtual environments before physical production. Uniform design, which requires the integration of functionality, comfort, aesthetics, ergonomics, and corporate identity, represents one of the most significant application areas of these technological developments. Modern digital tools such as Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), digital twin technologies, three-dimensional (3D) garment simulation systems, and artificial intelligence-supported visualization platforms contribute to more efficient and sustainable design processes. Furthermore, smart textiles and wearable technologies have expanded the functional capabilities of uniforms by incorporating sensing, monitoring, and adaptive performance features. This study investigates the integration of engineering and design within the framework of digital fashion and textile technologies. In addition, a woven fabric developed for a hostess uniform using Penelope CAD software is presented as a practical example of digital textile design. The findings demonstrate that the combination of engineering-based methodologies and creative design approaches contributes significantly to sustainability, innovation, product quality, and production efficiency in contemporary textile development.*

Keywords: *Digital Fashion, Uniform Design, Artificial Intelligence, Sustainability, Penelope CAD.*

DIGITALNA STRUKTURA MODE KROZ INTEGRACIJU INŽENJERSTVA I DIZAJNA

APSTRAKT: *Tekstil i industrija odeće doživljava duboku transformaciju koju pokreću digitalizacija, zabrinutost za održivost i brzi razvoj tehnologija veštačke inteligencije. Tradicionalni pristupi dizajnu i proizvodnji sve više se zamenjuju digitalnim sistemima koji*

omogućavaju dizajnerima i inženjerima da razvijaju, procenjuju i optimizuju proizvode u virtuelnim okruženjima pre fizičke proizvodnje. Dizajn uniformi, koji zahteva integraciju funkcionalnosti, udobnosti, estetike, ergonomije i korporativnog identiteta, predstavlja jednu od najvažnijih oblasti primene ovih tehnoloških razvoja. Savremeni digitalni alati kao što su kompjuterski potpomognut dizajn (CAD), kompjuterski potpomognuta proizvodnja (CAM), tehnologije digitalnog blizanca, trodimenzionalni (3D) sistemi simulacije odeće i platforme za vizuelizaciju zasnovane na veštačkoj inteligenciji doprinose efikasnijim i održivijim procesima dizajna. Pored toga, pametni tekstili i nosive tehnologije proširili su funkcionalne mogućnosti uniformi uključivanjem senzorskih, monitoring i adaptivnih performansi. Ova studija ispituje integraciju inženjerstva i dizajna u okviru digitalne mode i tekstilnih tehnologija. Pored toga, tkanina razvijena za uniformu stjuardese korišćenjem Penelope CAD softvera predstavljena je kao praktičan primer digitalnog tekstilnog dizajna. Rezultati pokazuju da kombinacija inženjerskih metodologija i kreativnih dizajnerskih pristupa značajno doprinosi održivosti, inovacijama, kvalitetu proizvoda i efikasnosti proizvodnje u savremenom razvoju tekstila.

Ključne reči: *Digitalna moda, dizajn uniformi, veštačka inteligencija, CAD sistemi, pametni tekstili, održivost, Penelope CAD.*

1. INTRODUCTION

The textile and apparel sector has become one of the industries most strongly influenced by digital transformation in recent decades. Developments in information technologies, computer engineering, material science, and artificial intelligence have significantly changed traditional product development processes. Activities that were once dependent on manual pattern preparation, repeated physical prototyping, and time-consuming production procedures are now increasingly supported by digital systems capable of simulating and optimizing products before manufacturing begins (Öğülmüş Özkum & Üreyen, 2020). Within this transformation, uniform design occupies a unique position due to its multidimensional requirements. Unlike conventional fashion products, uniforms must simultaneously satisfy functional, ergonomic, aesthetic, and institutional expectations. They serve as visual representations of corporate identity while also providing comfort, safety, durability, and performance for users operating in diverse professional environments. Consequently, the design of uniforms requires a multidisciplinary approach that integrates engineering principles, material science, textile technology, and design methodologies. At the same time, sustainability concerns have become increasingly important within the global textile industry. Growing awareness regarding environmental impacts, resource consumption, and waste generation has encouraged researchers and manufacturers to adopt more sustainable production methods. Recycled polyester, organic cotton, bio-based fibers, and environmentally friendly manufacturing processes have emerged as important alternatives to conventional production systems (Varol & Atalay

Onur, 2025). Digital technologies further support sustainability by reducing the need for physical samples and minimizing material waste throughout the product development cycle.

The convergence of digital technologies, engineering applications, and sustainable design strategies has given rise to the concept of digital fashion. Digital fashion extends beyond the simple use of computer software and encompasses virtual prototyping, digital twins, artificial intelligence-assisted design, smart textiles, and virtual garment systems. These developments are transforming fashion design from a largely intuitive and experience-based process into a data-driven and technology-oriented discipline (Atış & Can, 2024).

This study aims to examine the integration of engineering and design within the context of digital fashion and uniform development. Particular attention is given to digital design systems, artificial intelligence applications, sustainability considerations, and smart textile technologies. Furthermore, a practical case study involving the development of a hostess uniform fabric using Penelope CAD software is presented to demonstrate the practical implementation of these concepts.

2. DIGITAL TRANSFORMATION IN TEXTILE AND UNIFORM DESIGN

Digital transformation has fundamentally reshaped contemporary textile design and manufacturing processes. Computer-based technologies have introduced new methods for developing products, managing production workflows, and improving design accuracy. Computer-Aided Design (CAD) systems enable designers to create highly detailed digital models, while Computer-Aided Manufacturing (CAM) technologies facilitate the efficient transfer of design data into production environments (Öğülmüş Özkum & Üreyen, 2020).

One of the most significant advantages of digital transformation is the ability to evaluate garments before physical production. Traditionally, apparel development required multiple physical prototypes to assess fit, appearance, and functionality. This process consumed substantial amounts of material, labor, time, and financial resources. Today, advanced simulation systems enable designers to perform these evaluations virtually, significantly reducing development costs and environmental impacts.

Three-dimensional garment simulation software has become particularly important within the apparel industry. Programs such as CLO 3D and Optitex allow designers to visualize garments on virtual avatars and analyze their behavior under realistic conditions. Fabric drape, tension distribution, fit accuracy, and movement-related deformations can be evaluated before manufacturing begins.

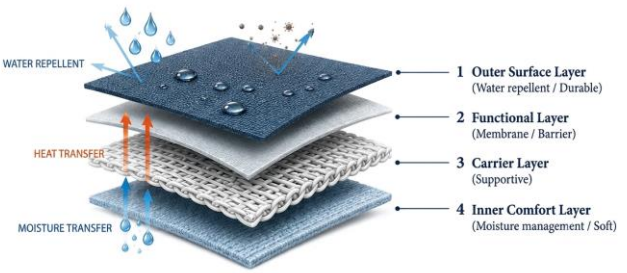


Figure 1: 3D Technical Textile Layer Structure

These capabilities are especially valuable in uniform design, where user comfort and ergonomic performance are critical considerations.

Another key development is the implementation of digital twin technology. A digital twin represents a virtual replica of a physical product that incorporates detailed information regarding material characteristics and performance parameters. In textile applications, - digital twins include fabric properties such as weight, elasticity, bending rigidity, thickness, and friction behavior. Through these systems, designers can perform realistic simulations and identify potential design problems before production (Bulat, 2022).

The integration of digital twins into uniform design offers several advantages. Pattern inaccuracies can be identified during the design stage, fit performance can be evaluated across different body types, and ergonomic analyses can be conducted through simulated movement scenarios. Such capabilities contribute to higher product quality while reducing development time and production costs.

As digital transformation continues to evolve, the relationship between engineering and design becomes increasingly interconnected. Successful textile product development now requires expertise not only in aesthetics and creativity but also in data analysis, simulation technologies, and engineering principles.

3. ARTIFICIAL INTELLIGENCE AND SMART TEXTILE TECHNOLOGIES

The rapid advancement of artificial intelligence (AI) has significantly influenced the textile and apparel industry. Beyond manufacturing automation, AI is now integrated into design, product development, quality control, trend forecasting, and consumer behavior analysis, making processes more data-driven, efficient, and innovative (Atış & Can, 2024).

AI enables designers to generate and evaluate multiple design alternatives rapidly. Through machine learning and generative systems, large datasets are analyzed to identify patterns, predict trends, and optimize solutions, assisting in color, material, and silhouette selection while accelerating decision-making. A key application is generative design, which uses predefined parameters and datasets to automatically create numerous design variations. Designers can evaluate hundreds of options to select the best solution based on aesthetic,

functional, and technical requirements, boosting both creativity and productivity (Atış & Can, 2024). AI is also widely utilized in manufacturing through computer vision systems that automatically detect fabric defects, color inconsistencies, and production errors. By identifying issues early, these systems improve product quality, reduce defective waste, lower costs, and increase operational efficiency. Alongside AI, smart textile technologies are vital in modern apparel development. Defined as advanced materials that sense environmental conditions, collect data, and respond to external stimuli, they represent a significant shift from passive garments to interactive, responsive systems. The application of smart textiles is prominent in military, healthcare, security, and uniform sectors. Sensor-integrated garments monitor physiological parameters like body temperature and heart rate, improving occupational safety in hazardous conditions through real-time monitoring and early warning signals.

Another key innovation is Phase Change Materials (PCM), which absorb, store, and release thermal energy in response to temperature changes. By regulating heat transfer between the body and the environment, PCM-integrated textiles enhance thermal comfort and wearer performance in fluctuating environments (Varol & Atalay Onur, 2025). Antibacterial and antimicrobial finishes, such as silver-ion treatments, have also become standard in modern uniform systems. These technologies inhibit bacterial growth on fabric surfaces to improve hygiene and safety, which is critical for contamination control in healthcare environments. The integration of AI and smart textiles is transforming traditional uniforms into multifunctional systems combining comfort, protection, communication, and monitoring. Modern uniforms are no longer just for visual identification, but are technologically enhanced products directly improving performance and well-being. Looking ahead, AI's role will expand into personalized garment development, predictive maintenance, and adaptive systems. Simultaneously, smart textiles will evolve into more sophisticated wearables interacting with digital environments, demonstrating the growing convergence of engineering, technology, and fashion design.

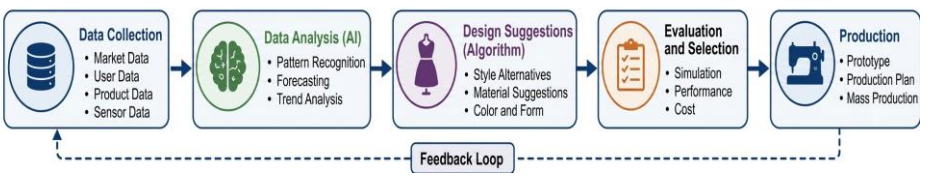


Figure 2 : AI-Powered Design Process

4. SUSTAINABILITY AND INDUSTRY 4.0 INTEGRATION

4.1 Sustainability in the Textile Industry

Sustainability has become one of the most important priorities within the global textile and apparel industry. The increasing environmental impact of conventional textile production, including excessive water consumption, chemical usage, energy demand, and waste generation, has encouraged researchers and manufacturers to seek more sustainable

alternatives. Consequently, recycled materials, organic fibers, and bio-based textile products have gained considerable attention in recent years (Varol & Atalay Onur, 2025).

4.2 Sustainable Materials in Textile Production

Recycled polyester has emerged as one of the most widely adopted sustainable materials in apparel manufacturing. Produced from post-consumer plastic waste, recycled polyester reduces dependency on virgin petroleum resources while contributing to waste reduction strategies. Similarly, organic cotton is cultivated without synthetic pesticides and fertilizers, resulting in lower environmental impacts compared to conventional cotton production. Bio-based fibers derived from renewable resources further support the transition toward circular production systems.

4.3 Digital Technologies and Sustainability

Digital technologies play a significant role in supporting sustainability objectives throughout the textile value chain. Traditionally, apparel development requires multiple physical prototypes before final production. Each prototype consumes materials, labor, energy, and transportation resources. Digital prototyping technologies reduce these requirements by enabling virtual product development and evaluation. Through 3D simulation systems, garments can be assessed, modified, and optimized digitally before manufacturing begins.

The reduction of physical sampling contributes directly to lower material waste, reduced water consumption, and decreased carbon emissions. Furthermore, digital workflows allow designers and manufacturers to identify production problems at earlier stages, thereby minimizing resource losses and improving overall efficiency (Varol & Atalay Onur, 2025).

4.4 Industry 4.0 Integration

The integration of Industry 4.0 technologies further strengthens sustainability initiatives. Industry 4.0 refers to the application of automation, data analytics, artificial intelligence, cloud computing, and interconnected production systems within manufacturing environments. Through real-time monitoring and intelligent decision-making systems, manufacturers can optimize production schedules, improve resource allocation, and enhance product quality.

Data-driven production systems enable continuous monitoring of machinery performance, material utilization, and production efficiency. This information supports predictive maintenance strategies, reduces downtime, and minimizes unnecessary resource consumption. As a result, Industry 4.0 technologies contribute to both economic efficiency and environmental sustainability. The combination of digitalization and sustainability represents a new paradigm for textile manufacturing. Rather than treating environmental responsibility and technological innovation as separate objectives, contemporary textile systems increasingly integrate both approaches into a unified framework. This

transformation is expected to play a critical role in the future development of sustainable and intelligent apparel production systems.

5. CASE STUDY: HOSTESS UNIFORM FABRIC DESIGN USING PENELOPE CAD

5.1 Functional and Aesthetic Requirements

To demonstrate the practical application of digital textile technologies, a woven fabric suitable for hostess uniforms was developed using Penelope CAD software. The design process focused on combining aesthetic requirements with functional performance criteria associated with professional uniform applications.

Hostess uniforms serve as visual representations of airline corporate identity and therefore require a professional, elegant, and reliable appearance. At the same time, they must provide comfort, durability, and ergonomic performance for employees who spend extended periods standing, walking, and interacting with passengers. Consequently, fabric selection and design involve both technical and aesthetic considerations. Several design criteria were established before the development process began. These included professional appearance, corporate identity compatibility, ergonomic comfort, breathability, flexibility, durability, wrinkle resistance, ease of maintenance, and suitability for digital simulation. The objective was to create a textile structure capable of supporting both visual and functional requirements.

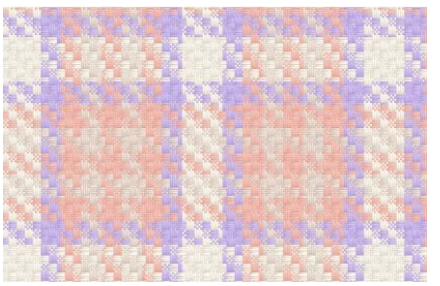
5.2Digital Fabric Development with Penelope CAD

In the scope of this study, Penelope CAD software was extensively utilized to design and simulate the woven fabric structure within a completely digital environment. This advanced computer-aided design platform allowed for the precise configuration of both warp and weft arrangements, including technical parameters such as yarn count, density, and twist direction. Crucial structural components, including complex weave patterns (such as twill, satin, or specialty jacquard effects), yarn characteristics, and high-fidelity color distributions, were systematically defined and simulated.

By transitioning the initial design phase to a digital interface, the platform enabled a comprehensive, microscopic evaluation of the fabric surface, seamless pattern repeats, inherent structural characteristics, and overall visual aesthetics prior to any physical manufacturing. One of the paramount advantages of implementing Penelope CAD in uniform design is its dual capability: it delivers hyper-realistic, three-dimensional fabric visualizations while simultaneously generating critical technical textile analyses, such as yarn consumption weights and structural integrity forecasts. Consequently, designers and engineers can critically evaluate color harmony, complex interlacing structures, and draping aesthetics without the immediate need for costly and time-consuming physical loom setups. Ultimately, this digital workflow drastically accelerates product development cycles, optimizes time-to-market metrics, and aligns with sustainable manufacturing principles by significantly reducing material, chemical, and yarn waste (Başaran, 2022).

Figure 3: Hostess uniforms at Penelope CAD

Here is a 3D product visualization, in the style of a textile catalog, showcasing multiple digital fabric samples created with Penelope, suitable for the professional and ergonomic requirements of hostess uniforms:



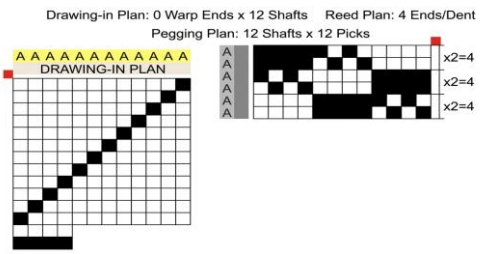


Figure 4: Digital visualization of the fabric design developed for the flight attendant (1)

Figure 5: Digital visualization of the fabric design developed for the flight attendant (2)

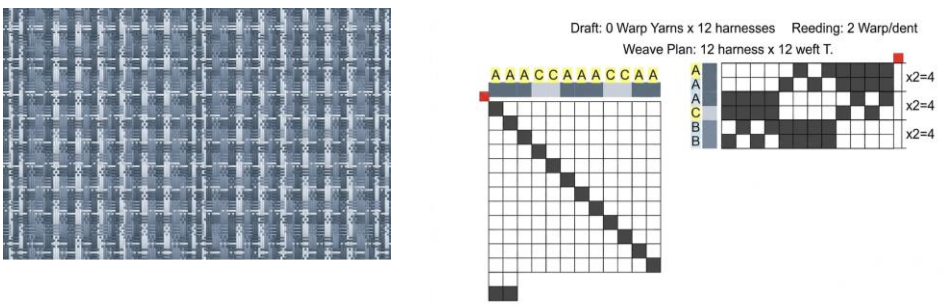


Figure 6: Digital visualization of the fabric design developed for the flight attendant (3)

5.3 AI-Supported Visualization

Following fabric development, artificial intelligence-supported visualization tools were used to generate digital representations of the fabric on hostess uniform concepts. These visualizations provided valuable insights regarding the potential appearance of the fabric within complete uniform systems. Front, back, and detailed garment views were created to assess color perception, surface characteristics, and overall aesthetic impact.

Although physical manufacturing and laboratory testing were beyond the scope of this study, the digital workflow demonstrated the effectiveness of integrating CAD technologies with artificial intelligence-supported visualization methods. The results suggest that digital textile development can significantly improve design efficiency while supporting sustainable production practices.

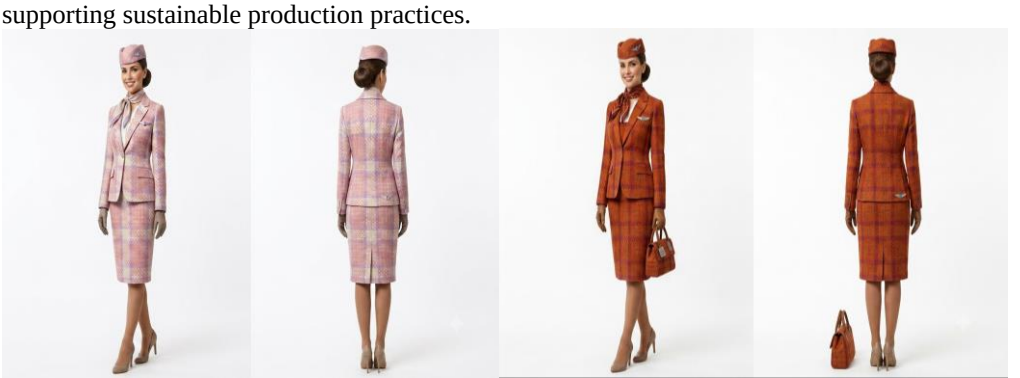


Figure 7: AI-Supported fabric design developed for the flight attendant

6. FUTURE PERSPECTIVES: DIGITAL FASHION AND VIRTUAL UNIFORM SYSTEMS

6.1 Digital Fashion and Virtual Environments

The emergence of digital fashion and virtual environments has introduced new opportunities for the textile and apparel industry. Advances in metaverse technologies, virtual reality platforms, and digital asset development have expanded the concept of clothing beyond physical products.

Digital fashion refers to garments designed exclusively for virtual environments. Unlike conventional apparel, digital garments exist only in digital spaces and can be utilized within virtual meetings, gaming environments, social media applications, and metaverse platforms. In the context of uniform design, virtual garments may serve important functions in digital workplaces and online communication systems. Organizations could develop virtual uniforms for employee avatars, maintaining corporate identity across both physical and digital environments. Such systems may become increasingly relevant as remote work and virtual collaboration continue to expand.

6.2 Artificial Intelligence and Future Design

Artificial intelligence is expected to play a central role in the future development of digital fashion. AI systems capable of analyzing consumer behavior, market trends, and user preferences will support more personalized and adaptive design processes. Predictive algorithms may enable organizations to anticipate future design requirements and respond more effectively to changing market conditions (Atış & Can, 2024).

6.3 Integration of Physical and Digital Textiles

Furthermore, advancements in wearable technologies, intelligent materials, and connected textile systems are likely to blur the boundaries between physical and digital products. Future uniforms may integrate sensing technologies, adaptive functionalities, and digital communication systems while simultaneously maintaining virtual representations within digital ecosystems.

These developments suggest that uniform design will increasingly evolve into a multidisciplinary field involving engineering, computer science, artificial intelligence, material technology, and fashion design.

7. CONCULUSION

The textile and apparel industry is undergoing a significant transformation driven by digital technologies, sustainability requirements, and artificial intelligence applications. The integration of engineering principles and design methodologies has created new opportunities for improving efficiency, product quality, environmental performance, and user experience.

Digital technologies such as CAD systems, CAM platforms, digital twins, and 3D garment simulation software have revolutionized traditional product development processes. These tools allow designers to evaluate products before manufacturing, reducing development costs and minimizing material waste. At the same time, artificial intelligence has expanded the possibilities of textile design through generative design systems, trend analysis, quality control applications, and personalized product development.

The increasing adoption of smart textiles further demonstrates the convergence of engineering and fashion. Sensor-integrated garments, phase change materials, and antimicrobial textile technologies are transforming conventional uniforms into multifunctional systems capable of supporting user performance, safety, and comfort.

The case study conducted using Penelope CAD software illustrated the practical benefits of digital textile development. Through virtual fabric design and AI-supported visualization techniques, textile products can be evaluated efficiently before physical production. Such approaches contribute to both economic efficiency and environmental sustainability.

Future developments in digital fashion, metaverse technologies, and artificial intelligence are expected to further strengthen the relationship between engineering and design. As a result, the concept of fashion will continue evolving toward more intelligent, sustainable, data-driven, and technologically integrated systems. The future of uniform design will depend increasingly on multidisciplinary collaboration that combines creativity, engineering expertise, digital innovation, and environmental responsibility.

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THE EVOLUTION OF FASHION AND ITS INTERPRETATION IN CONTEMPORARY DESIGN INSPIRED BY PROTECTIVE CLOTHING

Professional paper
DOI: 10.5937/CT_ITI26267R

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[c] ORCID ID: 0009-0002-2182-8520

ABSTRACT: *This paper analyzes the evolution of clothing throughout history, its application and function in different social and professional contexts, and its transformation into contemporary fashion design. The research examines changes in clothing, fashion trends, and the influences that have shaped fashion over time, including cultural, social, military, and health-related aspects. In addition to the theoretical analysis, the paper presents a practically realized contemporary fashion design inspired by historical and modern fashion influences.*

Key words: *fabric, clothing, history, trends, materials.*

EVOLUCIJA MODE I NJENA INTERPRETACIJA U SAVREMENOM DIZAJNU INSPIRISANOM ZAŠTITNOM ODEĆOM

APSTRAKT: *Ovaj rad analizira evoluciju odeće kroz istoriju, njenu primenu i funkciju u različitim društvenim i profesionalnim kontekstima, kao i njenu transformaciju u savremeni modni dizajn. Istraživanje razmatra promene u odevanju, modne trendove i uticaje koji su oblikovali modu kroz vreme, uključujući kulturne, društvene, vojne i zdravstvene aspekte. Pored teorijske analize, rad predstavlja i praktično realizovano savremeno modno rešenje inspirisano istorijskim i modernim modnim uticajima.*

Ključne reči: *tkanina, odeća, istorija, trendovi, materijali.*

1. INTRODUCTION

Fashion can be briefly defined as the continuous transformation of clothing styles and appearances adopted by specific groups of people. From a sociological perspective, it functions as a system of signs, a reflection of social values, and a means of shaping both collective and individual identity.

As an essential part of culture, fashion is expressed not only through clothing, but also through jewelry, artistic objects and other forms of visual and material culture. It is not limited to external appearance, but also represents a form of behavior and social communication. In this sense, fashion refers to a style of dressing characteristic of particular groups within specific historical periods and it is not universally accepted by all members of society.

Fashion exists across all historical periods and is characterized by constant change, fluctuations and cycles of rise and decline. It is also closely linked to major historical events such as wars, revolutions and other social transformations. This highlights the importance of understanding its underlying drivers and the factors that influence its development and emergence.

From initial concept development and sketching, through pattern making, garment production, market analysis and product distribution up to its final consumption, fashion clearly operates as a complex industry.

Today, fashion represents a form of personal expression and self-presentation in the contemporary world. It is fast-paced, dynamic and constantly evolving. It remains one of the most influential phenomena in Western civilization from the Renaissance period to the present day [1, 2].

Fashion and textile development have always been closely connected to historical events and social transformations, particularly wars and periods of crisis. Military conflicts have significantly influenced clothing design introducing elements of functionality, durability and uniformity that later became integrated into everyday fashion through the concept of the military style. Similarly, historical shifts in society have often dictated changes in materials, comfort and the overall purpose of clothing.

The influence of textiles extends beyond fashion into other fields, especially medicine. Historically, the need for protection, hygiene and functionality led to the development of specialized medical textiles. Textiles have always held a fundamental role in human life, evolving from basic protective materials in the past to highly specialized and multifunctional applications today, reflecting their wide presence and continuous importance across both historical and contemporary context [3, 4, 5].

In both historical and contemporary contexts, textiles demonstrate a continuous evolution, reflecting technological progress and societal needs. This confirms that fashion and textile design are not isolated aesthetic practices, but dynamic systems deeply intertwined with history.

In the contemporary context, fashion continues to evolve rapidly and remains highly responsive to social, cultural and global changes. In the period following the pandemic, significant shifts in consumer behavior and design priorities have become evident, with a growing emphasis on comfort and practicality in clothing, as well as the ongoing trend of

sustainable and circular fashion, which is highly relevant today. At the same time, there is an increasing awareness of the need to slow down the fashion cycle and move away from fast fashion tendencies. Greater attention is now being given to design approaches that prioritize quality, durability and sustainability. This shift reflects a broader effort within the industry to promote more responsible production and consumption, where long-lasting materials and thoughtful design play a key role in shaping the future of fashion [6, 7].

1.1. Historical Development of Fashion and Clothing

From the earliest periods of human history, the human body and clothing have been closely interconnected, whether for functiona, aesthetic or other reasons. Clothing can be defined as the protection of the entire body or specific body parts using various coverings made from natural or artificial materials. It is a characteristic feature of humankind and originates from the need to protect the body from harmful external, primarily climatic influences such as cold, rain, humidity and heat. Over time, clothing became a symbol of civilization and comfort, while the need to enhance appearance and emphasize its aesthetic function gradually emerged. This development contributed to frequent changes in styles and the evolution of fashion. It is well known that different historical periods were characterized by changing ideals of the human body, which contemporary fashion of each period attempted to follow, emphasize or even “correct.” In earlier times, fashion and dress codes were much stricter and less tolerant of deviation from established norms, whereas today’s fashion is significantly more liberal and diverse, supported by the development of various styles and subcultures that allow individuals greater freedom of choice. This has enabled people to express themselves more freely through the way they present their bodies. Throughout history, the development of costume follows two distinct lines, closely connected to two main categories of clothing: women’s and men’s fashion. From a contemporary perspective, the most relevant developmental line can be understood through the differentiation between masculine and feminine clothing, particularly reflected in the two basic garment types: trousers and skirts.

Research in the field of costume history clearly indicates that, in the past, men occupied a dominant position in terms of variety and ornamentation in clothing. In many historical periods, men’s garments were often more richly decorated than those worn by women.

Furthermore, the study of costume history highlights the need to challenge traditional prejudices related to the strict division between male and female clothing. When considering broader classifications, some costume historians propose an alternative division of clothing into “tight-fitted” and “loose or draped” forms. Within such a framework, contemporary clothing can largely be placed within the category of fitted garments. There are also various theories regarding the fundamental motives for wearing clothing, which are generally classified into several different groups. Before the mid-19th century, most clothing was custom-made. With the invention of the sewing machine and the rise of industrial production in the 20th century, clothing began to be mass-produced in standardized sizes, expanding retail availability.

Today, the fashion industry operates globally, with design, production, and sales often taking place in different countries. In the 21st century, fashion has become highly seasonal

and fast-changing, strongly influenced by media and social networks, which make trends immediately accessible.
Increased living standards, mobility and the demand for appearance have further driven the growth of ready-made clothing, making fashion a highly profitable global industry supported by modern technology and automated production processes. [8, 9, 10].

1.2. Clothing as a protective system, functional and aesthetic use

Clothing has historically functioned as a protective system, developed primarily to shield the human body from environmental conditions such as cold, heat, rain and humidity. In its earliest forms, clothing was made from natural materials and served a strictly functional purpose, ensuring human survival and adaptation to different climates and living conditions.
Over time, the protective role of clothing evolved alongside social and technological development. Different historical periods introduced new materials, construction techniques and design approaches that improved both the durability and functionality of garments. Clothing gradually became not only a means of physical protection but also a reflection of social status, cultural identity and technological progress.
The functional use of clothing expanded further with industrialization, when mass production and standardized sizing made protective garments more accessible. In modern times, the concept of protective clothing extends beyond everyday wear and includes specialized applications designed for specific working environments and conditions, emphasizing safety, performance and comfort.
This evolution demonstrates that clothing is not only an aesthetic or cultural element, but fundamentally a functional system that continues to adapt to human needs throughout history. The human instinct for survival led to the early development of protective clothing, initially in very primitive forms. Protective clothing, understood as a type of "covering" garment, was used to shield the body from physical harm.
In prehistoric times, humans protected themselves by attaching bundles of grass to their clothing in order to conceal and defend themselves from aggressive animals.
The earliest evidence of protective clothing suggests that the first garments were made from animal skins, with some of the oldest findings discovered in Europe and Western Asia. Until the Industrial Revolution in the 19th century, clothing was mainly used as protection against weather conditions.
With the development of civilization, protective equipment evolved from simple wooden shields to more advanced metal forms of protection. During the Middle Ages, metal armor became the primary means of protection for knights. In the medieval and Renaissance periods, armor was regarded as the most effective form of defense against contemporary weapons and was also considered an elaborate form of body decoration.
From the 14th to the 16th century, protective clothing reached a high level of effectiveness, as it was shown to adequately meet the defensive needs of that time based on contemporary analyses. However, the emergence of firearms significantly reduced the effectiveness of traditional armor. To maintain sufficient protection, armor became increasingly heavy,

reaching weights of up to approximately 50 kg, which greatly limited mobility and placed a considerable burden on the wearer.

Leather garments were originally used as underlayers beneath armor, but over time multiple layers of leather began to be used directly as protective clothing, offering improved flexibility and ease of movement. This period also marked the beginning of discussions on the balance between protection and comfort, particularly mobility.

The period from the 17th to the 19th century, characterized by the Industrial Revolution, introduced significant transformations in the design, materials and overall function of protective clothing.

With the Industrial Revolution, there was a significant increase in the use of protective clothing against industrial hazards such as heat, fire, explosions and chemical substances.

The beginning of the 21st century marks a period of innovation in textile science and new materials, leading to the transformation of traditional clothing functions into advanced technologies and modern textile production systems [11].

From the mid-20th century onwards, textiles increasingly began to be used not only for aesthetic and clothing purposes but also for functional applications. This shift marked the beginning of a new phase in textile development, where performance and protection became equally important as design.

Functional textiles represent an important segment of contemporary textile science and industry, focusing on materials designed not only for aesthetic purposes but primarily for specific performance and protective functions. Functional textiles are developed to meet diverse requirements such as protection, durability and adaptability to different environmental and working conditions.

Technical and high-performance textiles are widely used in sectors such as healthcare, military protection, sportswear and industrial applications. These materials are engineered to provide enhanced properties, including resistance to heat, chemicals, mechanical stress and biological factors. In addition, modern developments in textile engineering have led to the creation of smart textiles that incorporate advanced technologies for improved functionality. Special-purpose clothing design emphasizes the integration of material properties with ergonomic and functional requirements, ensuring both protection and usability. Research in this field highlights the importance of selecting appropriate fabrics and construction techniques to achieve optimal performance in demanding conditions. The development of functional and protective textiles has also significantly influenced the healthcare sector. Alongside industrial and military applications, textiles increasingly began to be used for medical and hygienic purposes, contributing to improved protection, safety and comfort in healthcare environments. The advancement of textile technologies enabled the production of materials with specialized properties suitable for medical garments, protective equipment and other healthcare-related applications.

In contemporary textile science, medical textiles represent an important field focused on combining functionality, protection, hygiene and user comfort. Their application became particularly significant during periods of global health crises, when the importance of protective and functional clothing was further emphasized. During the COVID-19 pandemic, the importance of medical and protective textiles became especially evident, as

protective clothing and face masks became essential elements of everyday life. This period further accelerated the development of innovative textile materials focused on safety, functionality and sustainability [7, 12].

1.3. Transformation of protective clothing into contemporary everyday fashion

Throughout fashion history, protective and functional clothing has continuously influenced contemporary fashion design. Garments originally created for military and protective purposes gradually evolved beyond their primary function and became a significant source of inspiration in modern fashion. Elements such as durability, patterns, oversized silhouettes and details have been reinterpreted within contemporary clothing design and adapted for everyday use.

Today, military clothing has had a strong influence on fashion trends due to its recognizable forms and symbolic association with strength, discipline and trends. Over time, these characteristics were transformed into aesthetic features widely present in contemporary fashion collections. Fashion designers increasingly combine functionality with aesthetics, creating garments that respond not only to practical needs but also to contemporary lifestyles and personal expression. This transformation demonstrates how protective clothing can evolve from a purely functional system into a source of inspiration for innovative and modern fashion design.

Rei Kawakubo is one of the fashion designers who is known for redefining beauty and challenging fashion conventions, she has become one of the most influential figures in contemporary design since the 1970s**.** Punk and military influences are recurring themes in the work of Rei Kawakubo, particularly evident in her Fall 1994 "Metamorphosis" collection. In this collection, military inspiration is strongly expressed through shrunken, boiled wool jackets combined with voluminous skirts, creating a distinctive contrast in silhouette and proportion. Rei Kawakubo frequently incorporates military and punk influences into her designs, reinterpreting uniform elements through deconstructed silhouettes and conceptual garment structures. Her work for Comme des Garçons often explores the relationship between clothing and the body, transforming protective and military-inspired forms into contemporary fashion expressions [13]. A recent example of the reinterpretation of military aesthetics in contemporary fashion is the Rei Kawakubo Autumn/Winter 2025 collection for Comme des Garçons Homme Plus, presented in Paris under the theme "To Hell With War". In this collection, Kawakubo deconstructs military iconography, challenging its symbolic meaning and reinterpreting its role in contemporary fashion. The collection breaks down traditional military elements such as uniforms, camouflage patterns, and structured forms, transforming them into abstract and conceptual design expressions. Military helmets are reimagined as sculptural avant-garde headpieces, emphasizing the tension between functionality and artistic interpretation.

Through this approach, Kawakubo continues her exploration of military symbolism, transforming functional and authoritative references into critical fashion statements that question war, identity and uniformity in contemporary society [14, 15].

Figure 1. Rei Kawakubo, *Comme des Garçons Homme Plus AW25 Collection*. Source: Jeanson (2025), CRASH Magazine https://www.crash.fr/rei-kawakubo-declares-to-hell-with-war-in-provocative-aw25-collection/

2. EXPERIMENTAL

2.1. Design inspired by Rei Kawakubo

2.1.1. Conceptual connection

The presented sketch (Fig. 2) interprets the theoretical principles of Rei Kawakubo into an experimental menswear design solution. The inspiration is reflected through the reinterpretation of protective clothing elements and their transformation into a contemporary silhouette that combines functionality with conceptual expression.

The design process focused on adapting protective garment characteristics through deconstructed layering and kimono-inspired construction. Structural balance is achieved through the interaction between controlled form and relaxed volume, creating visual tension between protection and vulnerability.

Figure 2: New model inspired by Rei Kawakubo military-inspired design

The olive-green palette was selected to reference military and protective garments, while the asymmetrical red accent introduces contrast and symbolic disruption. The wide belt element emphasizes restraint and stability, reinforcing the relationship between body control and structural protection.

Figure 3: Color palette used for the new model

Through this approach, the model applies Kawakubo's design methodology by transforming recognizable protective references into an abstract contemporary menswear form, where traditional construction principles are reconstructed to communicate resistance, transformation and critical reinterpretation. The technical sketch of the new model is presented in Fig. 4.

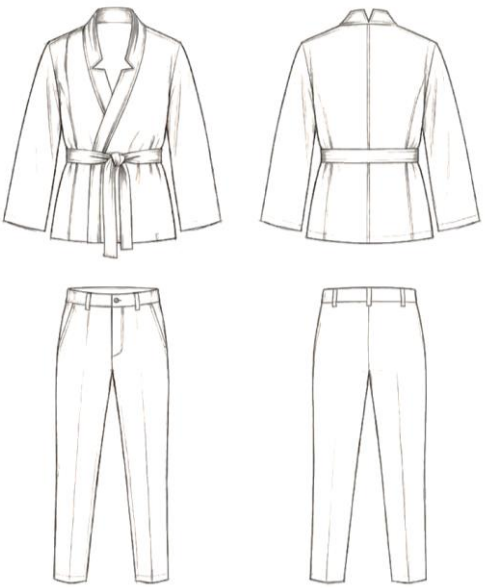

Figure 4: Technical sketch of the newly designed model

Following Rei Kawakubo's critical visual language, this design transforms military aesthetics from a symbol of power into a narrative protection. The kimono pattern serves as a cultural foundation, reimagined through military deconstruction to create a dialogue between tradition, conflict and resistance.

3. RESULT AND DISCUSSION

3.1 New redesigned model of men's clothes, inspired by protective clothes

This experimental menswear design explores the reinterpretation of protective clothing through a contemporary fashion language. The model is developed through the transformation of functional garment elements into an expressive silhouette that balances structure and character.

The upper part of the design is based on a kimono-inspired wrap construction, chosen for its architectural simplicity and adaptability. This traditional form is restructured with protective clothing references, creating a layered visual effect that suggests security,

restraint and comfort. The wide black belt emphasizes the waistline while symbolizing control and structural stability.

The olive-green color palette directly references military and protective uniforms, reinforcing associations with discipline. In contrast, the asymmetrical red textile element introduces visual disruption and symbolic tension, representing vulnerability, resistance and the traces of conflict.

The trousers maintain a narrowed functional silhouette, allowing movement while preserving the utilitarian character of the composition. Additional details such as fingerless gloves and heavy footwear further strengthen the protective aesthetic and support the concept of reconstructed defense garments adapted for contemporary menswear. The model was created using textile waste generated as cutting leftovers from a garment manufacturing company, with the aim of promoting sustainable approaches in contemporary fashion design. The selected materials, originally considered production waste, were reinterpreted and incorporated into a new fashion concept, demonstrating the potential for their aesthetic and functional reuse. During the design and production process, special attention was given to the efficient utilization of textile materials, pattern arrangement in order to minimize additional waste and achieve a more sustainable production approach. This process emphasizes the importance of circular design principles and responsible material consumption within the contemporary fashion industry.

The experimental process focused on deconstructing conventional protective clothing forms and reconstructing them through kimono-inspired pattern cutting, resulting in a hybrid design that challenges the boundaries between military clothes and modern fashion expression.

In a broader historical context, this design also reflects the original role of clothing as protection. Throughout history, garments were not primarily defined by aesthetics, but by their functional necessity - serving as a barrier against environmental conditions, offering protection. In this sense, protective clothing represents one of the earliest foundations of dress culture.

Today, these utilitarian origins are revisited and reinterpreted within contemporary fashion practices. Rather than serving purely functional needs, protective garments are transformed into conceptual and aesthetic resources. In this design, that transformation becomes central: historical notions of protection are translated into a modern visual language where functionality and fashion expression coexist within a single experimental menswear silhouette [16, 17].

Figure 5. The final appearance of the model (front and rear)[1]

4. CONCLUSION

Fashion represents a dynamic phenomenon that continuously evolves in response to historical, social, technological and cultural changes. Throughout history, clothing has fulfilled not only aesthetic functions but also protective, functional and symbolic roles, reflecting the needs and values of different societies and historical periods. The

[1]Source: Shtip Fashion Days 2025 https://www.instagram.com/shtipfashiondays/p/DAlHQPwIlmS/
Model designed by student Emil Vezenkov. Part of the collection “Eclectic” 2025. Mentor: Assoc. Prof. Dr. Sanja Risteski.

development of textiles and clothing has been closely connected to wars, industrialization, technological progress and contemporary global challenges, all of which have significantly influenced the transformation of fashion design.

The research presented in this paper confirms that protective clothing has had an important impact on the development of contemporary fashion. Elements originally created for military have gradually been transformed into aesthetic and conceptual components within modern fashion design. Contemporary designers increasingly reinterpret functional garments through new design approaches, creating a balance between protection, functionality and visual expression.

The practical realization of the contemporary menswear model presented in this paper demonstrates how protective clothing can serve as inspiration for innovative fashion design. Through the use of textile waste generated as cutting leftovers from garment production, the model also emphasizes the importance of sustainability, circular design principles and responsible material utilization in the contemporary fashion industry.

This research highlights that fashion is not only a reflection of aesthetic trends, but also a complex system shaped by history, technology, functionality and human needs. The reinterpretation of protective clothing within contemporary design confirms the continuous connection between past and present, as well as tradition and innovation in modern fashion practice.

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FROM ANTHROPOMETRY TO SPATIAL PATTERN DESIGN: A 3D FRAMEWORK FOR WOMEN'S GARMENT CONSTRUCTION

Professional paper
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***ABSTRACT*:** *Garment construction is a complex process that integrates body morphology, design principles, and production techniques. Traditional pattern-making methods, based on two-dimensional models and standardized sizing systems, often fail to reflect the variability and three-dimensional nature of the human body. This paper proposes a spatial framework that combines anthropometric data, body shape classification, and pattern construction for women's garments. It emphasizes the transformation of 2D patterns into 3D forms and highlights the limitations of conventional approaches. The findings indicate that incorporating spatial and volumetric considerations improves garment fit, functionality, and adaptability, contributing to more efficient and personalized clothing design.*

Keywords: *Anthropometry; garment construction; pattern making; body shape classification; spatial design; sizing systems.*

OD ANTROPOMETRIJE DO PROSTORNOG DIZAJNA KROJA: 3D OKVIR ZA KONSTRUKCIJU ŽENSKE ODEĆE

APSTRAKT: *Konstrukcija odeće je složen proces koji integriše morfologiju tela, principe dizajna i tehnike proizvodnje. Tradicionalne metode izrade krojeva, zasnovane na dvodimenzionalnim modelima i standardizovanim sistemima veličina, često ne uspevaju da odražavaju varijabilnost i trodimenzionalnu prirodu ljudskog tela. Ovaj rad predlaže prostorni okvir koji kombinuje antropometrijske podatke, klasifikaciju oblika tela i konstrukciju krojeva za žensku odeću. Naglašava transformaciju 2D krojeva u 3D oblike i ističe ograničenja konvencionalnih pristupa. Rezultati ukazuju da uključivanje prostornih i volumetrijskih razmatranja poboljšava pristajanje odeće, funkcionalnost i prilagodljivost, doprinoseći efikasnijem i personalizovanijem dizajnu odeće.*

Ključne reči: *Antropometrija; konstruisanje odeće; izrada krojeva; klasifikacija oblika tela; prostorni dizajn; sistemi veličina.*

1. INTRODUCTION

From birth, humans constantly interact with textiles, and the visual language of clothing reflects social needs, cultural identity, and personal expression. Historically, textile production has been intricately linked to tradition, trade, religion, and cultural exchange. The fundamental purpose of clothing is protection, making it one of the oldest industries in human history. Today, clothing also plays a significant role in expressing individuality and psychological well-being. Consumers choose garments not only based on design, materials, and comfort, but also on how well they match their personal preferences and body shape [1-6]. The garment industry is a complex system where design, technology, and human factors interact. Clothing is not only a functional necessity but also a form of social communication and personal expression. Modern challenges such as fast fashion, mass production, and increasing consumer demands for personalization have intensified the need for improved garment fit and design accuracy [7-11]. The fashion industry is a highly globalized and dynamic sector, constantly evolving and influencing various aspects of modern lifestyles. Its value chain extends across multiple countries, reflecting its global impact. The term fashion is associated with style, dress, and clothing, particularly in Western societies [12, 13]. Research shows that fashion is shaped by art, architecture, culture, and social life, leading to the creation of the latest trends [14-17]. It is a form of communication and expression of collective preferences and lifestyles. However, fashion is flexible, as styles evolve and are adopted at different rates depending on age, location, and socio-economic conditions [18].

In response to changing consumer preferences toward functionality and digital lifestyles [19-21], the digital economy has accelerated the transformation of the fashion industry through advanced technologies [22-28]. Digital transformation involves company-wide changes and the emergence of new business models, in which digital fashion integrates fashion with ICT tools [29]. Technologies such as artificial intelligence, robotics, e-commerce, and social media are key drivers of industry growth [30]. The fashion industry has shifted from retailer-driven to consumer-driven (fast fashion) production [31], characterized by short cycles, rapid demand changes, and complex supply chains [32]. Consequently, the value chain has evolved toward faster, more flexible production systems, covering mass production, limited editions, and haute couture segments [33].

Today, consumers are more aware of their clothing choices, seeking information about the origins and conditions [34]. Innovation and technological advancement play a key role in the apparel industry, particularly in production processes and in meeting diverse customer demands [35-37]. The adoption of Industry 4.0 technologies is essential for supporting competitiveness, enabling faster production, greater flexibility, and more efficient resource use [38,39]. These systems support intelligent and adaptable manufacturing, especially important for developing economies reliant on production and export [40]. Successful implementation requires investment in infrastructure, education, and policy support [41],

while European industries show varying levels of adoption [42]. Additionally, modern 2D/3D CAD systems are increasingly used to improve pattern design and overall production efficiency [43-45].

A key issue in garment production is the mismatch between standardized sizing systems and the diversity of human body shapes. Anthropometric measurements provide the foundation for garment construction, but traditional approaches often do not fully address body variability. These developments raise an important question: how can garment design better respond to the variability of the human body? The aim of this paper is to analyze the relationship between anthropometric body dimensions, body shape classification, and pattern construction principles, and to propose a spatial framework for improving garment design.

2. THEORETICAL BACKGROUND

2.1 Anthropometry

Body contours are shaped and defined through silhouettes that visually reflect fashion history. The relationship between the body, textiles, and clothing is complex and interdependent, forming a key consideration for designers. Textile and fashion design are intricately connected disciplines, often inseparable in practice [46]. Therefore, a fundamental requirement for creating high-quality garments is a thorough understanding of human anatomy, body shape, and proportions, supported by fields such as anatomy, anthropology, and morphology. Anthropometry studies the measurement and proportions of the human body and is a fundamental tool in garment construction. Key body measurements include height, bust, waist, and hip circumferences, which are used to define garment dimensions and sizing systems. Standardized systems such as ISO and EN sizing frameworks are developed to classify body dimensions and enable mass production. However, these systems cannot fully capture the variability of human body shapes.

2.2 Anthropometric Body Dimensions in Garment Construction

Human body proportions are found through anatomy, which studies the form and structure of body parts, and they vary depending on gender and age. Historically, efforts have been made to define rules for measuring these proportions. In garment construction, the head length is commonly used as a module to find overall body proportions. The human body consists of the head, neck, torso, arms, and legs, and its vertical proportions are typically divided into three parts: head, torso, and legs. Compared to the male body, the female body is generally more delicate, with narrower shoulders, a smaller chest, wider hips, and a more defined waist. It also contains a higher proportion of adipose tissue, resulting in smoother and more rounded body contours [47]. In relation to this, aanthropometry represents a fundamental scientific basis for garment design, as it enables the translation of human body dimensions into functional clothing structures. The most important anthropometric parameters used in garment construction are shown in Table 1 and Figure 1:

Table 1: Body dimensions

Primary dimensions:	Secondary dimensions:
Body height (H)	Shoulder width
Bust circumference (B)	Back length
Waist circumference (W)	Arm length
Hip circumference (Hc)	Neck circumference

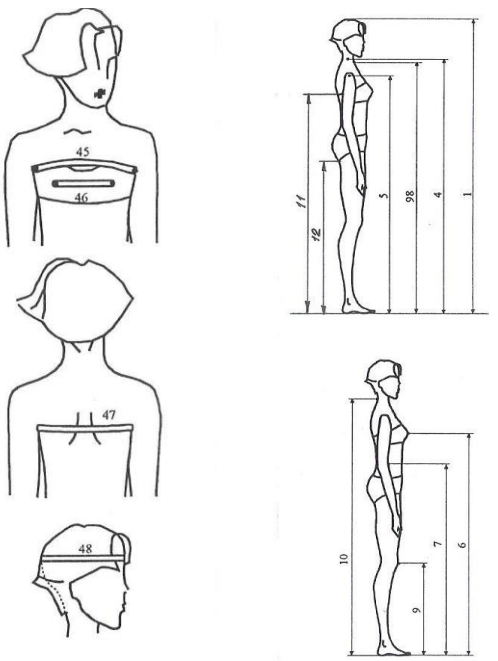

Figure 1: Main anthropometric measurement points used in garment construction

The relationship between primary and secondary anthropometric measurements forms the basis for proportional garment construction and grading systems. These measurements are used to derive construction measurements, which are not directly measured but calculated based on proportional relationships. However, it is important to note that body proportions are not fixed. They vary depending on age, gender, and individual morphology. For this reason, garment construction does not rely only on direct measurements, but also on proportional relationships between them. For example, the relationship between bust, waist, and hip measurements strongly influences garment silhouette, while vertical proportions affect the overall balance of the design. In addition, secondary measurements such as shoulder width and arm length play a significant role in ensuring comfort and mobility. Therefore, a good understanding of human anatomy and proportions is essential for achieving both functional and well-fitted garments.

2.3 Women's Body Shape Classification

In addition to measurements, body shape is another crucial factor in garment design. Several studies have shown women's bodies vary significantly in their proportions and change throughout different life stages [48]. Common body shapes include hourglass, pear (triangle), inverted triangle, rectangle, and round (apple) (Figure 2). Each body type requires specific adjustments in garment construction, particularly in areas such as bust shaping, waist shaping, and hip allowance. Body shape classification is essential in garment design, as it allows adaptation of pattern construction to different morphological characteristics. For instance, pear-shaped bodies often require additional space in the hip area, while inverted triangle shapes may need adjustments in shoulder width. In contrast, rectangular body types usually require added shaping to create visual balance. This suggests that body shape classification is not only descriptive but also highly practical. It allows designers to adapt patterns in a more targeted and effective way.

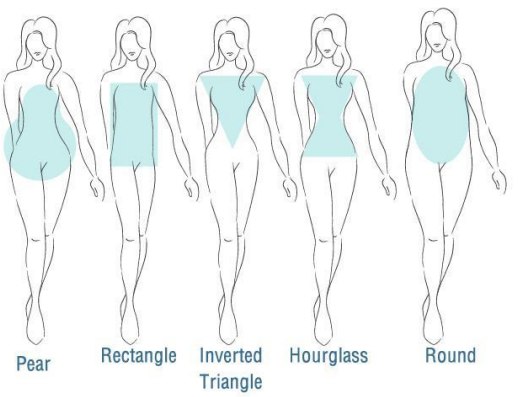

Figure 2: Common women's body shape classifications and their morphological characteristics

2.4 Spatial approach to garment construction

Garment construction can be better understood when viewed from a spatial perspective. The human body is a three-dimensional structure with complex geometry, while garment patterns are typically developed as two-dimensional surfaces. This creates a fundamental design challenge: how to transform flat textile pieces into a form that fits a three-dimensional body. In practice, this transformation involves several steps, including proportional scaling, geometric adaptation, and structural shaping. Anthropometric data provide the necessary input, while pattern-making techniques define how the material is distributed around the body. From this perspective, garment construction can be considered a form of applied spatial engineering. The goal is not only to match dimensions, but also to ensure that the garment follows the natural form and movement of the body.

2.5 Design and Pattern-Making Principles

Fashion design gives identity and value to products and is a fundamental process in the fashion supply chain. In the era of fast fashion, brands must design efficiently due to rapid changes and high pressure on production, delivery, and inventory management [49]. The product development process, led by designers, includes idea generation, fabric selection, sketching, prototyping, fit evaluation, cost calculation, production planning, and grading [50]. Successful product launches depend not only on market knowledge but also on understanding technical and technological aspects of garment production and marketing requirements [51]. This process is generally divided into two stages: design (creative development) and production (implementation of solutions) [52].

Pattern construction represents a key stage in the garment development process. It translates body measurements into a set of technical drawings that define the shape and structure of the garment [53–56]. It includes determination of construction measurements, development of base patterns and modeling and adaptation. Two main approaches are commonly used. The flat pattern method (2D), which is widely applied in industrial production, is valued for its efficiency and consistency. On the other hand, the draping method allows designers to work directly on a mannequin, providing greater flexibility and precision, especially for complex designs. Today, CAD/CAM systems play an increasingly important role in this process. They make it possible to develop patterns more quickly, reduce errors, material waste, and improve overall production efficiency [57-60]. Nevertheless, it is important to emphasize that both traditional and digital methods still depend on the experience and skills of the pattern maker [61].

3. METHODOLOGICAL APPROACH (ANALYTICAL FRAMEWORK)

3.1 Linking Body Shapes and Pattern Construction

In practice, there is a clear relationship between body measurements and pattern construction. For example, bust circumference figures out garment width, while waist measurements influence shaping through darts and seams. Hip measurements affect the volume of lower garments, and body height defines vertical proportions. However, these relationships are not purely mechanical. They must be adjusted depending on body shape. This means that pattern construction involves both measurement-based calculations and interpretative decisions. For instance, more ease may be needed for round body shapes, while more structured shaping is often needed for rectangular forms. This confirms that garment design is not only a technical process, but also an adaptive one. A systematic relationship between body measurements and pattern construction can be defined:

- Bust circumference → decide garment width;
- Waist circumference → defines shaping and darts;
- Hip circumference → affects lower garment volume;
- Body height → influences vertical proportions.

Different body shapes require specific pattern modifications (Table 2).

Table 2: Linking Body Shape Types and Pattern Adjustments

Body Shape Type	Key Characteristics	Pattern Adjustments
Hourglass	Balanced proportions (bust & hips), defined waist	Standard proportional construction; minimal adjustment needed
Pear (Triangle)	Wider hips, narrower shoulders	Increase hip allowance; reduce upper width; adjust waist shaping
Inverted Triangle	Wider shoulders; narrower hips	Reduce shoulder width; add volume in hip area
Rectangle	Similar bust; waist and hip measurements	Add darts and shaping elements to create waist definition
Round (Apple)	Fuller midsection, less defined waist	Increase ease in waist area; reduce tight shaping; ensure comfort fit

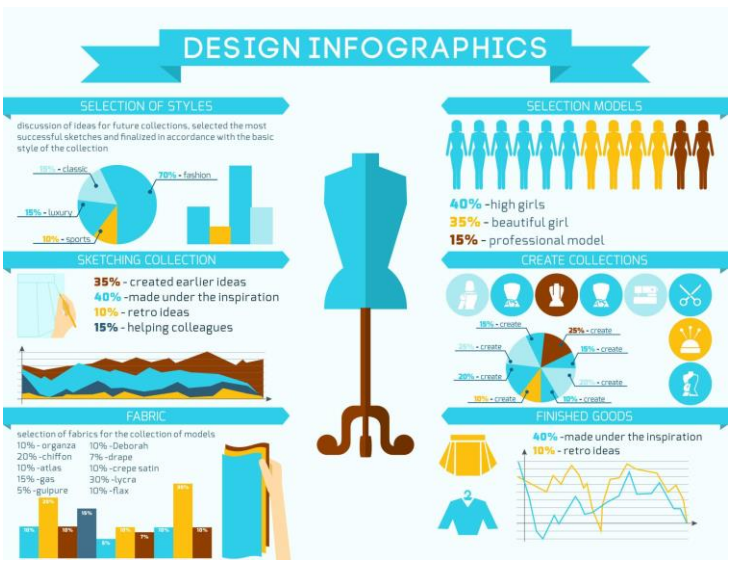

Figure 3: Design development and pattern adjustment workflow in garment construction

Figure 3 presents the workflow of design development and pattern adjustment according to body shape and design requirements. It includes concept creation, sketching, pattern modification, and fit evaluation. The figure demonstrates how technical and creative processes are integrated in garment construction.

These relationships form the basis for constructing different garment types. The transformation of anthropometric measurements into garment patterns requires the application of construction rules such as ease allowance, dart manipulation, and

proportional scaling. These rules ensure that garments not only fit the body but also allow movement and comfort.

3.2 Spatial Perspective in Garment Construction

Fit, comfort, and size are key factors in clothing design and are considered essential for garment quality, influencing customer satisfaction and purchase decisions [62–64]. Proper fit depends on body measurements, shape, and proportions [65]. The development of standardized sizing systems emerged with mass production in the late 19th and early 20th centuries and has been extensively studied since the 1940s [66]. From a spatial perspective, the human body can be understood as a complex three-dimensional structure, while garment patterns are two-dimensional representations. Garment construction therefore involves transforming flat textile surfaces into forms that correspond to body geometry. This process requires geometric adaptation, proportional scaling, and structural adjustment based on anthropometric data and pattern-making principles. In this context, garment construction can be interpreted as a spatial transformation process, where the objective is to achieve a balance between body form, functionality, and comfort. The spatial transformation process in garment construction is illustrated in Figure 4.

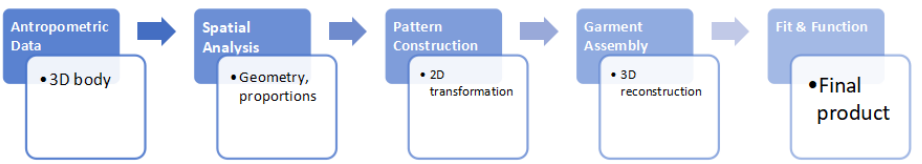

Figure 4: Spatial transformation process in garment construction

3.3 Limitations of 2D Models and Proposed 3D Volumetric Classifications

Traditional 2D modeling is limited by its reliance on the X–Y plane, which flattens the human body and ignores Z-axis depth (front and back volume). As a result, it often produces “flat-pattern distortion,” where garments meet width requirements but fail to accommodate true body depth, leading to tension and poor fit. To address these limitations, a 3D volumetric framework is proposed (Figure 5), focusing on depth and body dynamics. The Projected Keystone accounts for anterior–posterior torso depth, ensuring proper accommodation of body thickness. The Bi-Segmented Helix considers rotational asymmetry between the upper and lower body, reflecting natural movement. The Expanding Arc describes three-dimensional body curvature, particularly in areas with increased volume. This approach enables more accurate and adaptive garment construction by integrating spatial body characteristics.

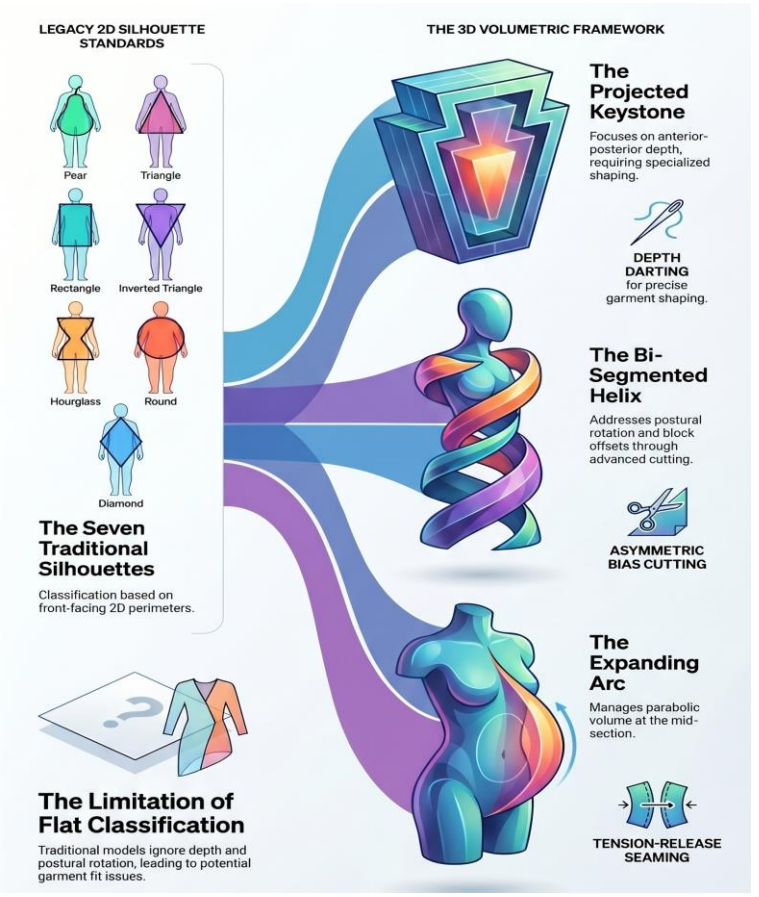

Figure 5: 3D volumetric framework

The transition from 2D pattern models to 3D volumetric approaches is influenced by morphological variations and body mechanics. In this context, garment construction requires moving beyond flat-pattern logic toward more adaptive, multi-dimensional design strategies. In practice, this may include the use of multi-directional darting to accommodate body depth and redistribute fabric according to areas of greater volume, such as the chest or abdomen. Similarly, seam placement can be adjusted to follow natural body movement and structural lines, improving both fit and comfort. These approaches suggest that incorporating three-dimensional body characteristics into pattern design can enhance garment performance and reduce fitting issues. At the same time, more accurate pattern construction may contribute to reduced material waste by minimizing the need for excessive allowances.

4. DISCUSSION

The findings highlight that garment construction is a multidimensional process requiring the integration of anthropometry, body morphology, and spatial design principles. While traditional methods provide standardized procedures, they are often insufficient for addressing the diversity of modern consumers.
Standard sizing systems simplify production but fail to account for variations in body depth, posture, and volume distribution. Body shape classification improves pattern adaptation by providing an intermediate framework between measurements and design.
The proposed spatial approach enhances garment construction by incorporating three-dimensional body characteristics.

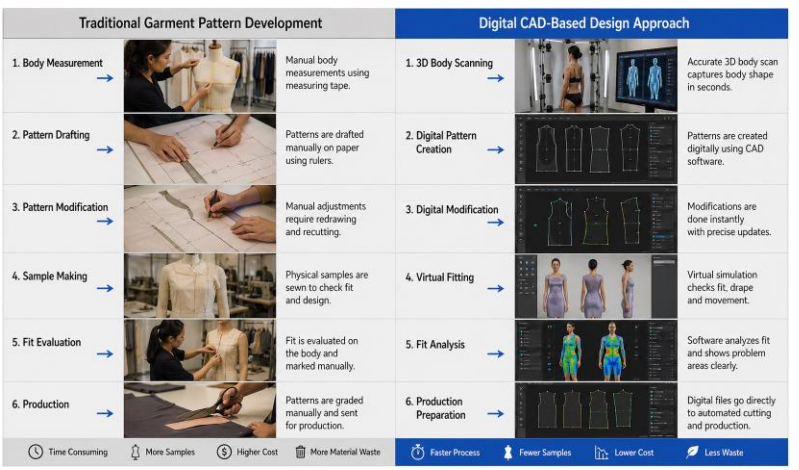

Figure 6: Comparison between traditional garment pattern development and digital CAD-based design approaches

In addition, digital technologies such as 3D body scanning and virtual fitting systems offer significant potential for improving accuracy and efficiency.
Improved garment fit can also contribute to sustainability by reducing return rates, minimizing material waste, and increasing product longevity.
The Figure 6 compares conventional garment development methods with modern digital approaches. Traditional processes involve manual measurements, flat pattern drafting, and physical prototyping, whereas digital methods use 3D body scanning, CAD/CAM systems, and virtual fitting technologies for faster and more precise garment production.

5. CONCLUSION

This research substantiates the necessity of reconceptualizing garment construction as a spatially oriented, multidisciplinary design process grounded in anthropometric science,

body morphology analysis, and three-dimensional spatial reasoning. Although anthropometric measurements constitute the foundational dataset for pattern development, they are inherently limited when applied in isolation. Their integration with body shape classification and spatial interpretation of the human form is essential for achieving enhanced structural accuracy, ergonomic performance, and functional adaptability in garment design. Furthermore, the incorporation of advanced digital technologies-particularly 3D body scanning, computer-aided design (CAD), and virtual prototyping systems-significantly extends the precision and efficiency of the design process, while simultaneously contributing to greater sustainability and reduced material waste within the apparel industry. In conclusion, garment construction should be understood as an interdisciplinary domain at the intersection of science, engineering, and design. The spatial approach proposed in this study provides a robust analytical framework for the development of individualized and innovative women's clothing systems. Future research should prioritize empirical validation through 3D scanning methodologies and computational simulation within virtual fitting environments.

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CLASSIFICATION AND EVALUATION OF CHARACTERISTIC SHAPES OF MATERNITY PONCHOS USING A MACHINE LEARNING ALGORITHM

Professional paper
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ABSTRACT: *The present study presents results of classification and evaluation of poncho shapes for pregnant women using radius-vector functions and machine learning algorithms. 30 digital images were analyzed, based on which six main shapes were identified: rectangular, oval, round, asymmetric, hooded, and V-shaped. Using feature selection methods, the most informative features were determined, and the models were grouped using Euclidean metrics and compared with expert assessment. The results show that the most common are V-shaped, oval, and hooded models, which form about 80% of the examples and are distinguished by comfort, functionality, and aesthetics. Based on the analysis, a universal adaptive poncho model was developed, combining the preferred shapes and structural elements, providing comfort and freedom of movement for different stages of pregnancy and the postpartum period. The study offers guidelines for the modern design of maternity clothing.*

Keywords: *Maternity Poncho, Shape Classification, Machine Learning, Image Analysis, Adaptive Clothing.*

KLASIFIKACIJA I PROCENA KARAKTERISTIČNIH OBLIKA PONČA ZA TRUDNICE KORIŠĆENJEM ALGORITMA MAŠINSKOG UČENJA

APSTRAKT: *U ovoj studiji su predstavljeni rezultati klasifikacije i evaluacije oblika ponča za trudnice korišćenjem funkcija radijus-vektor i algoritama mašinskog učenja. Analizirano je 30 digitalnih slika, na osnovu kojih je identifikovano šest glavnih oblika: pravougaoni, ovalni, okrugli, asimetrični, sa kapuljačom i u obliku slova V. Koristeći metode selekcije karakteristika, određene su najinformativnije karakteristike, a modeli su grupisani korišćenjem euklidskih metrika i upoređeni sa procenom stručnjaka. Rezultati pokazuju da su najčešći modeli u obliku slova V, ovalni i sa kapuljačom, koji čine oko 80% primera i odlikuju se udobnošću, funkcionalnošću i estetikom. Na osnovu analize, razvijen je univerzalni adaptivni model ponča, koji kombinuje preferirane oblike i strukturne*

elemente, pružajući udobnost i slobodu kretanja za različite faze trudnoće i postporođajni period. Studija nudi smernice za savremeni dizajn odeće za trudnice.
Ključne reči: *Pončo za trudnice, Klasifikacija oblika, Mašinsko učenje, Analiza slike, Adaptivna odeća.*

1. INTRODUCTION

Adaptive and versatile maternity clothing is an important segment in the modern fashion industry, where comfort, functionality, and aesthetics are important [1, 2]. The poncho has emerged as a preferred model due to its loose fit and ability to provide space and comfort for different body types, including expectant mothers [3].
The influence of traditional forms and motifs characteristic of the poncho is traced in a number of ethnic and cultural contexts, such as the Mexican and Navajo styles, which contribute to the development of modern design solutions [4].
There is no systematic classification of poncho forms that simultaneously takes into account comfort, space, and aesthetics.
Most of the existing research focuses on the traditional and cultural aspects of the poncho, but not on its applicability for pregnant women in modern design. This makes it difficult to select optimal models that meet the specific needs and preferences of this consumer segment.
The development of clothing classification and evaluation technologies based on machine learning and digital images provides new perspectives for analyzing characteristic shapes and selecting optimal clothing models [5]. Radius-vector functions are used as a tool for extracting geometric features, and the selection of shape coefficients allows for precise classification and objective assessment of silhouettes [6].
The aim of the study is to classify and evaluate shapes of maternity ponchos based on radius-vector functions and machine learning. By integrating expert assessment, a universal and adaptive model for clothing suitable both during pregnancy and in the postpartum period is sought.

2. MATERIAL AND METHODS

Digital images of garments from accessible Internet sites were used. After downloading, the files were processed with an online artificial intelligence tool, Copilot (Microsoft Corp., Redmond, WA, USA). This tool extracted only the garments from the photos and gave them a new look, different from the original. The background of the image was removed. The final files were saved in *.PNG format.
Radius-vector functions were used to analyze the characteristic shapes of maternity clothes and their images. From each image, 5 form coefficients, FI1, FI2, FI3, FI4, and FI5, were calculated.
The form indices have the following form [7]:

$$FI1 = \frac{1}{\pi}\int_0^{\pi} \frac{|R(\theta) - R(\pi - \theta)|}{\bar{R}} d\theta \quad (1)$$

$$FI2 = \frac{R(\theta_{max})}{\bar{R}} \quad (2)$$

$$FI3 = \frac{R_{max}}{\bar{R}} \quad (3)$$

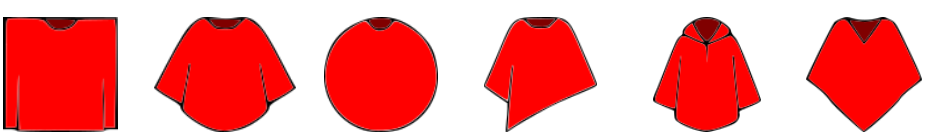
$$FI4 = \frac{1}{2\pi}\int_0^{2\pi} \frac{|R_t(\theta) - R_0(\theta)|}{\bar{R}_0} d\theta \quad (4)$$

$$FI5 = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (R'(\theta) - \bar{R}')^2 d\theta} \quad (5)$$

where R(θ) is a radius-vector function; $\bar{R}$ is the average value of R(θ); R_{max} is the largest radius, relative to the center of gravity of the object; the angle θ changes in the interval θε[0, 2π]; $R_t(\theta)$ is the current value of the radius; $R_0(\theta)$ is the initial radius; R'(θ) is the first derivative of the radius-vector function R(θ) with respect to the angle θ.
Using the methods RReliefF, FSRNCA and SFCPP [8], the three most informative coefficients were selected. These three shape coefficients were used to represent the clothing models in three-dimensional space.
An algorithm with a Euclidean distance function was used to compare the real images with the characteristic shapes of clothing for pregnant women. This distance (d) was calculated using the following formula:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (6)$$

where x_1, y_1 and z_1 are coordinates in the three-dimensional space of the characteristic shape of the clothing for pregnant women; x_2, y_2 and z_2 are coordinates of the shape indices of the real image of the clothing.The characteristic shapes of ponchos are shown in Figure 1. The images were downloaded from accessible literature sources [2, 3, 4], then redrawn and stylized. Six basic shapes of ponchos are presented, indicated by a code. These include rectangular (SP1), oval (SP2), round (SP3), asymmetrical (SP4), hooded (SP5) and V-shaped (SP6). The indicated ponchos have their own shape and method of manufacture, which allows them to look different and be worn in different ways.



a) rectangular **SP1** | b) oval **SP2** | c) circle **SP3** | d) asymmetrical **SP4** | e) with a hood **SP5** | f) V-shaped **SP6**

Figure 1: Characteristic shapes of ponchos

Table 1 lists the websites from which the poncho images were downloaded. For each model, the specific website from which the image was downloaded, the date the site was accessed, and the number of photos taken from it are listed. The analysis covers a total of 30 images collected from various online fashion, retail, and vintage clothing platforms, such as HSN, Farfetch, Vestiaire Collective, eBay, and others.

Table 1: Description of the clothing photos used

Model number	Internet source	Accessed on	Number of images
P1,P2	https://www.hsn.com/	05.08.2025	2
P3,P4,P5	https://mania.bg	12.01.2026	3
P6,P7,P8,P9	https://www.farfetch.com/	12.01.2026	3
P10,P11	https://us.vestiairecollective.com/	12.01.2026	3
P12,P13, P14	https://www.aboutyou.bg/	11.08.2025	3
P15	https://www.ebay.com/	21.07.2025	1
P16	https://www.baltini.com/	21.07.2025	1
P17	https://www.johnlewis.com/	18.07.2025	1
P18	https://thefoldline.com/	15.08.2025	1
P19,P20	https://vintagebymisty.com/	15.08.2025	2
P21	https://www.lyst.com/	18.08.2025	1
P22	https://echonewyork.com/	18.08.2025	1
P23, P24,P25	https://answear.bg/	18.08.2025	3
P26	https://www.theredclosetdiary.com/	16.08.2025	1
P27	https://newlife-baby.com/	16.08.2025	1
P28,P29	https://www.faire.com/	22.07.2025	2
P30	https://shopstyle.bg/	16.08.2025	1
-	-	**Total**	**30**

Figure 2 presents the poncho models used in the study, each with an identifier from P1 to P30. The images have a variety of shapes, colors and cuts. Among them, ponchos with fringes, hoods, asymmetrical silhouettes and various decorative elements stand out, as well as combinations of different shapes. Poncho models can be grouped by shape. V-shaped (P1, P2, P13, P14, P18, P19, P22, P28) with classic or softened silhouettes. Rectangular and straight (P6, P7, P8, P16, P21, P25, P27, P30) with varying degrees of structure. Oval and round (P3, P5, P9, P10, P11, P15) with smooth lines and decorative accents. Asymmetrical/combined (P4, P12, P17, P20, P23, P26, P29) with slanted, elongated or mixed shapes and additional details.

The study involved three subject matter experts (S1, S2, and S3). They were individually surveyed using a structured form containing the images of the analyzed models (P1–P30). For each image, they indicated belonging to one of the six predefined forms (SP1–SP6), without prior information about the results of the algorithmic classification. The obtained scores were used for comparative analysis with the automatic results and to assess the accuracy and limitations of the applied methodology.

Figure 2: Poncho clothing models

3. RESULTS

Using the selection methods RReliefF, FSRNCA, and SFCPP, it was found that in all three choices, the most informative compared to the other shape indices are FI2, FI4, and FI5. Figure 3 shows the grouping of poncho models according to characteristic shapes, determined by distance functions. The results of the distance functions show a strongly unbalanced distribution between the shapes. The most common is SP5 (with a hood) – 13 models (over 40%), followed by SP2 (oval) with 7 models and SP4 (asymmetrical) with 5 models, while SP6 (V-shaped) is represented by only 3 models, SP3 (round) with 1, and SP1 (rectangular) also with 1 model. The equating of most shapes to SP5 is due to the fact that the shape indices more easily capture the general volumetric shape and roundness

characteristic of a hooded poncho. They do not distinguish well enough specific features of shapes such as the V-shaped line (SP6), rectangular geometry (SP1), or circular shape (SP3).

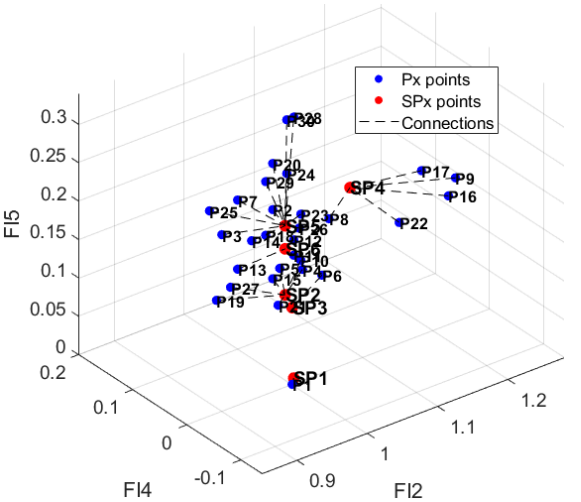


Figure 3: Correspondence to an image of a poncho with a characteristic shape

Table 2 shows the grouping of the characteristic shapes according to the results of the distance function and the classification of three experts in the subject area.

Table 2: Correspondence of an image of a poncho with a characteristic shape

P	D	S1	S2	S3	P	D	S1	S2	S3
P1	SP1	SP6	SP1	SP6	**P17**	SP4	SP4	SP5	SP4
P2	SP5	SP6	SP2	SP6	**P18**	SP5	SP6	SP6	SP6
P3	SP5	SP2	SP3	SP2	**P19**	SP2	SP6	SP1	SP6
P4	SP2	SP4	SP4	SP4	**P20**	SP5	SP4	SP2	SP2
P5	SP2	SP3	SP5	SP2	**P21**	SP2	SP1	SP3	SP6
P6	SP3	SP5	SP6	SP1	**P22**	SP4	SP2	SP4	SP2
P7	SP5	SP1	SP2	SP1	**P23**	SP5	SP4	SP5	SP4
P8	SP4	SP1	SP1	SP1	**P24**	SP5	SP5	SP6	SP5
P9	SP4	SP1	SP3	SP6	**P25**	SP5	SP1	SP1	SP6
P10	SP2	SP2	SP4	SP2	**P26**	SP5	SP6	SP2	SP6
P11	SP6	SP3	SP5	SP4	**P27**	SP2	SP1	SP3	SP1
P12	SP6	SP5	SP6	SP4	**P28**	SP5	SP2	SP4	SP4
P13	SP6	SP6	SP1	SP4	**P29**	SP5	SP6	SP5	SP5
P14	SP5	SP2	SP2	SP4	**P30**	SP5	SP1	SP6	SP1
P15	SP2	SP2	SP3	SP6	-	-	-	-	-
P16	SP4	SP1	SP4	SP6	-	-	-	-	-
P-poncho; D-distance; Sx-specialist; Px-poncho number; SPx-basic poncho shape									

Compared to the manual classification, where SP1 and SP6 are much more strongly represented, an underestimation of these groups is seen here, which is an indication that the distance function used has limited sensitivity and leads to incorrect classifications. The material from which the poncho is made also affects the perception and classification of the shape. This explains the differences in the opinions of the experts or incorrect recognitions by the algorithm.

Figure 4 shows a graph of the percentage of correspondence between poncho images and characteristic shapes. The most common shapes are the V-shaped, oval, and hooded, forming a total of almost 80% of all observed models, which clearly shows market preferences and contemporary design trends. These shapes are particularly suitable for pregnant women, as they provide sufficient space and comfort while maintaining the elegant shape of the garment. The asymmetrical shape is also found and has the potential to create modern design solutions suitable for pregnant women. The rectangular and round shapes are less common, with the round one being defined as a niche segment. The presence of combined shapes and models with additional details indicates an interest in innovation and variations on the basic shapes, which can also be adapted for maternity clothing.

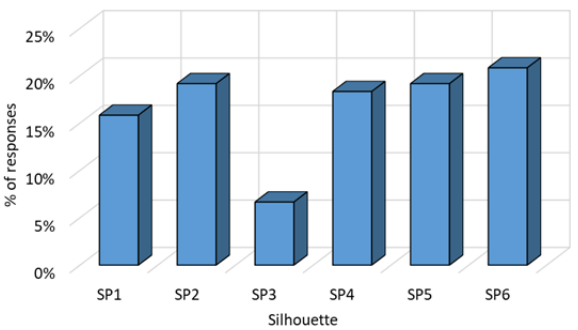


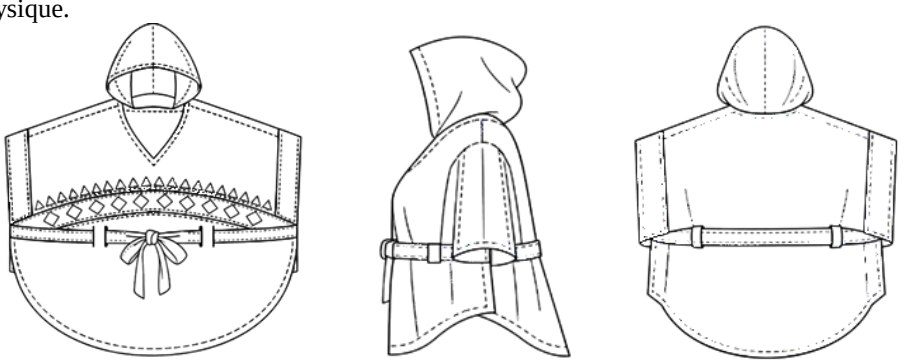
Figure 4: Percentage of responses matching poncho images with characteristic shapes

From the analyses made, it can be summarized that when developing a real poncho model, the priority should be on the most popular shapes and combinations between them, while less common ones, such as the round one, can be used for niche or limited products, especially if combined with additional details or specific materials.

The proposed poncho model combines an oval shape, a V-neck, and a hood for maximum comfort and style. It is made of soft wool, cashmere, or jersey with ethnic motifs and short fringes; it offers a loose cut, suitable for different body types, including pregnant women. Universal and adaptable, the model is complemented by asymmetrical and decorative elements for a contemporary look and meets current trends in clothing design for expectant mothers.

The poncho construction (figure 5) includes a rectangular or oval-shaped base fabric and universal dimensions (width 120–140 cm, length 80–100 cm), providing a loose and comfortable fit. A V-neck is formed in the front (20–30 cm wide, 25–35 cm deep), and a separately constructed hood of two symmetrical parts (25–30 × 35–40 cm) adds

functionality. Asymmetric or decorative panels (10–15 × 60–80 cm) located in the shoulder area are also included for a modern look. For adaptability, the model is complemented by a belt (length 120–180 cm, width 3–6 cm), which passes through hidden nuts located on the side and/or on the back, providing stability and the ability to adjust according to the physique.



a) Front b) Side c) back

Figure 5. Textile patterns of developed poncho model

The AI generative model Copilot was used to visualize the proposed poncho model. This visualization is presented in Figure 6. The images demonstrate options for how the garment is worn. The three options are with a hood and belt, a frontal view with emphasized drapery, and a silhouette on a figure in a natural stance. The visualization emphasizes the loose cut, decorative edges, and adaptability of the model.

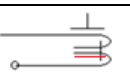
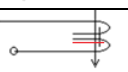
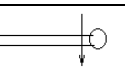
Figure 6. AI visualization of a poncho model

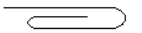
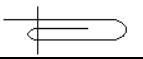
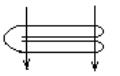
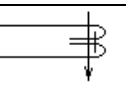
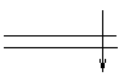
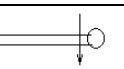
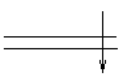
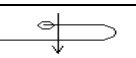
Technological operations for making a poncho with a removable belt are proposed, systematized in table 3.

The main fabric is cut according to the pattern (oval or rectangular), marking all the structural elements – neckline, hood, decorative panels, and places for attaching the belt.

The hood is made of two symmetrical details (25–30 × 35–40 cm), joined along the upper edge, processed with an overlock, and sewn to the neckline.
The V-shaped neckline is edged with a strip of the main fabric, reinforced with a connecting and decorative seam. The side edges are finished with an overlock, and fringes (5–8 cm) can be added for decoration if needed, along with ethnic designs and extra details on the edges.
The belt is made to individual sizes, hemmed and reinforced if necessary, and the edges can be decorated. For fixing, eyelets/nuts from the main fabric are provided, located laterally and/or on the back, ensuring silhouette adjustment. Depending on the design solution, either vertical eyelets or nuts are used, with one option excluding the other.
In the final stage, the poncho is ironed, the symmetry and quality of the seams are checked, and the belt is adjusted to the product with adjustments if necessary for optimal comfort and a finished look.

Table 3: Technological sequence for making a poncho for pregnant women

№	Operation name	Stitch symbol	Stitch type	Note
00.00	Cutting and release	-	-	-
00.01	Rolling, cutting, assembling and numbering	-	-	-
00.01	Gluing of cut necks and cut neckline with knitted backing, nuts and belt (if necessary)	-	-	Iron
00.03	Preparation for work and release of the tufts	-	-	-
01.00	Front parts - main fabric	-	-	-
01.01	Passing a connecting stitch row on the strip of main fabric with the neckline cut		301	At the beginning and at the end of the tightening
01.02	Ironing to the length of the product		-	Iron
01.03	Passing a decorative stitch row		301	-
01.04	Ironing the front part	-	-	Iron
01.05	Marking the location of the buttonholes (for the belt)	-	-	Handmade
02.00	Back parts - main fabric	-	-	-
02.01	Marking the location of the buttonholes (for the belt)	-	-	Handmade
03.00	Hood	-	-	-
03.01	Passing a connecting stitch row on the inner seams of the hood		301	At the beginning and at the end of the tightening
03.02	Passing a 3-end overlock on the inner seams of the hood		504	-

№	Operation name	Stitch symbol	Stitch type	Note
03.03	Bending the outer edge of the hood		-	Iron
03.04	Passing by folding the hem of the hood		301	-
03.00	Nuts/buttonholes for the belt	-	-	-
03.01	Making and cutting belt nuts		301	-
03.02	Smoothing	-	-	-
03.03	Making buttonholes on the front and back of the poncho (according to the width of the belt)	-	-	-
03.00	Belt	-	-	At the beginning and at the end of the tightening
03.01	Passing connecting inner seams of the belt		301	Handmade
03.02	Turning	-	-	At the beginning and at the end of the tightening
03.03	Passing front seams of the belt		301	Iron
03.04	Smoothing the belt	-	-	-
04.00	Assembly	-	-	At the beginning and at the end of the tightening
04.01	Attachment of the hood to the neckline		301	-
04.02	Passing 3 final overlocks on inner seams of the hood and neckline		504	-
04.03	Sewing ethnic motifs and asymmetrical panels to the main fabric		301	-
04.04	Passing the hem		301	-
05.00	Finishing operations	-		-
05.01	Thread cleaning		P	-
05.02	OTK	-	P	-
05.03	Final T&C	-	Ю, П	-
05.04	Dimension control of the finished product	-	P	Iron
05.05	Labeling	-	P	-

4. DISCUSSION

Designing maternity clothing requires a combination of ergonomic comfort, anthropometric adaptability, and aesthetics. The analysis of the developed poncho model against the literature confirms its functional validity and innovative nature.
The main constructive volume (width 120-140 cm, oval silhouette) corresponds to the requirements of Das [9] for freedom of movement and absence of pressure in the abdominal area. The technological allowance allows adaptation to changes in body dimensions without limiting comfort.
Functional adaptability is realized through an adjustable belt (up to 180 cm) and positioned nuts in the waist and back area, which complements the observations of Quintero Rodriguez, C., & Troynikov [10] on transforming clothing. This solution provides control over the silhouette during the different stages of pregnancy and the postpartum period.
The aesthetic characteristics of the model complement the results of Parras-Burgos et al. [11], as the V-neck and the asymmetrical decorative panels (60–80 cm) visually balance the silhouette and contribute to a modern look. Additional decorative elements enhance the individual character of the product without compromising functionality.
The proposed poncho model integrates ergonomic and aesthetic principles, confirming that through adjustable structural elements and appropriate geometry, clothing with sufficiently high functionality and visual value for the modern pregnant woman can be achieved.

5. CONCLUSION

This paper proposes a classification and evaluation of poncho shapes for pregnant women by integrating radius-vector functions, feature selection, and machine learning algorithms. The analysis of 30 images showed trends in contemporary adaptive clothing design, with the most preferred models being hooded, oval, and V-shaped silhouettes.
Based on the results obtained, a universal adaptive poncho model was developed, presented through its construction and manufacturing technology. The poncho model combines the most preferred shapes and structural elements – oval base, V-shaped neckline, hood, decorative panels, and adjustable belt. The model provides comfort, functionality, and aesthetics for the different stages of pregnancy and the postpartum period.
Visualization using an AI model confirms the applicability of the structural solutions and demonstrates various wearing options.
The comparison between automatic classification and expert assessment shows limitations of the distance function used, especially in distinguishing specific shapes such as rectangular, circular, and V-shaped. This highlights the need to expand the set of geometric and visual features for more precise classification of clothing shapes.

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SESSION III
MANAGEMENT

THE INFLUENCE OF TECHNOLOGICAL DEVELOPMENT ON MANAGEMENT INNOVATIONS - AN EXAMPLE OF THE TEXTILE INDUSTRY

Review paper
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ABSTRACT: *This paper studies the impact of technological development on management innovations, with special attention being paid to management innovations in the textile industry. The work is based on the fact that in modern conditions, technological development is the basis and main driver of economic and social development in general, as well as that this process implies changes in all spheres of activity, including in the sphere of business management. The study of the subject matter begins with a brief overview of the development and changes of management from its origins to the present day, pointing to the fact that in the era of the new technological revolution, the application of nanotechnologies, biotechnology, industrial ecology, etc. it is necessary to apply new, sometimes completely different, business management methods that are in accordance with the new economic conditions. The main characteristics of innovative management methods in modern companies are new approaches to management, i.e. to conducting business activities, changes in the organizational structure of the company, encouragement of creativity and innovation of employees, simultaneous development of strategic adaptability and operational efficiency and the like. In the final part of the paper, management innovations that must be implemented in the textile industry sector are pointed out, and which concern, first of all, adequate management of the environmental, economic and social aspects of the textile production process.*

Keywords: *technological development, business management, management innovations, textile industry, business efficiency, ecology, human resources.*

UTICAJ TEHNOLOŠKOG RAZVOJA NA INOVACIJE MENADŽMENTA - PRIMER TEKSTILNE INDUSTRIJE

APSTRAKT: *U ovom radu proučava se uticaj tehnološkog razvoja na inovacije menadžmenta, pri čemu se posebna pažnja posvećuje inovacijama menadžmenta u tekstilnoj industriji. U radu se polazi od činjenice da je u savremenim uslovima tehnološki razvoj osnova i glavni pokretač privrednog i društvenog razvoja uopšte, kao i da dati proces podrazumeva promene u svim sferama delatnosti, pa i u sferi poslovnog upravljanja. U proučavanju predmetne problematike polazi se od kratkog pregleda razvoja i promena menadžmenta od nastanka do danas, ukazujući na činjenicu da je u eri nove tehnološke revolucije, primene nano tehnologija, biotehnologija, industrijskih ekologija i sl. neophodno primeniti nove, nekada potpuno drugačije, metode poslovnog upravljanja koje su u skladu s novim uslovima privređivanja. Kao glavne karakteristike inovativnih metoda upravljanja u savremnim preduzećima ističu se novi načini upravljanja, tj. obavljanja posla, promene organizacione strukture preduzeća, podsticanje kreativnosti i inovativnosti zaposlenih, istovremeni razvoj strateške prilagodljivosti i operativne efikasnosti i slično. U završnom delu rada ukazuje se na inovacije menadžmenta koje je neophodno sprovesti u sektoru tekstilne industrije, a koje se tiču, pre svega, adekvatnog upravljanja ekološkim, ekonomskim i socijalnim aspektima procesa proizvodnje tekstilnih proizvoda.*

Ključne reči: *tehnološki razvoj, poslovno upravljanje, inovacije menadžmenta, tekstilna industrija, efikasnost poslovanja, ekologija, ljudski resursi.*

1. INTRODUCTION

Technology is one of the most significant factors in the modern development of humanity. The level of technological development corresponds to the level of the overall socio-economic development of a country. The application of modern technological achievements changes all aspects of human life, leading to large and rapid changes in the ways people live and conduct business. As a result, modern business conditions are characterized by large and rapid changes, but also discontinuity, which further complicates business conditions. This, on the other hand, permanently relativizes the position of economic entities, introducing uncertainty into their operations, against which they are fighting in the process of their growth and development. Growth and development in developed countries today are predominantly based on scientific and research activity, creativity and innovation in all areas of business. Changed business require the application of adequate management methods that are aligned with changes in the business environment. In this sense, it is necessary to introduce new, innovative management methods that would enable more efficient operations. These methods should be based on innovation, flexibility and appropriate motivation of employees. Each economic sector must take care of this in accordance with the specific conditions of its business. The textile industry, which undoubtedly represents a significant economic sector, provides wide opportunities for the introduction of management innovations, since a green transition should be made in this sector in order to realize its long-term sustainable development.

2. IMPACT OF TECHNOLOGICAL DEVELOPMENT ON CHANGES IN BUSINESS CONDITIONS

Although technology and technological development are as old as human society, it can be said that only since the First Industrial Revolution has there been a significant qualitative change in the nature of their influence on the entire socio-economic development of humanity. Modern technological achievements today represent the most powerful means of competitiveness of highly developed countries and the basis of their monopoly position in many areas of international economic and political relations. The level of technological development is also one of the most important criteria for dividing countries into highly developed and underdeveloped, because the new scientific and technological revolution, which was created by the long-term work of a large number of scientists and experts in all fields of activity, is today a necessary condition for faster development of all national economies. As a result, developed countries are investing increasing amounts of resources in scientific and research work, while the slower development of underdeveloped countries is largely determined by the underdevelopment of their scientific and research work and the low level of technological development.

The impact of technological development is very broad and manifests itself in changes in the way of production and technological procedures, the appearance of new products, materials, changes in the sphere of marketing and distribution of products, as well as in changes in the expectations and demands of consumers [1]. On the other hand, technological changes to a considerable extent cause an increase in the dynamism of the environment, which causes changes in business conditions, their greater uncertainty and unpredictability. As a result, business conditions become discontinuous, and the desire for globalization of the market and the world economy manifests itself, and as a result, the pressure on companies for constant diversification and rapid changes in production programs increases. It can be said that the new technological revolution and the information revolution, as an integral part of it, also led to the economic revolution. In such conditions, new ways of market economy, new methods of creating and using resources, as well as new value systems were created [2].

Technological development, however, represents not only the basis but also a prerequisite for the socio-economic development of every country and its economic subjects, as it:

- significantly contributes to the increase in the rate of economic growth,
- increases the productivity of economic entities,
- improves the country's position in the international division of labor and
- contributes to more complete satisfaction of the population's needs.

As a result, countries and economic entities that do not achieve adequate technological development permanently worsen their competitive position, which significantly slows down their development [2].

The development and application of the latest technological achievements implies continuous growth in the amount of knowledge of the economy and its entities, as a result of which modern economies are called knowledge economies and knowledge-based economies. The knowledge economy means an economy that bases its development on the

production, distribution and use of knowledge [3]. Knowledge-based economies use knowledge in all their economic sectors and activities, which has contributed to the change and expansion of their economic structure, so that knowledge-based economies become knowledge-driven economies. A high level of development of science, as well as an educated population, represent an adequate basis for faster technological development, so that between the sphere of knowledge, education, science, technology and economic development, a relationship of solid connection and interdependence is formed [4].
The development of the knowledge economy is conditioned, above all, by the development of information and communication technologies. As a result, global competition intensified due to the reduction of communication costs and the increase in communication speed. Changes also occurred on the demand side, since there was an increase in income, a change in consumer tastes and attitudes, etc. [5].
Practice shows that knowledge-based economies have wider opportunities for development and are more adaptable to changes in business conditions (Figure 1).

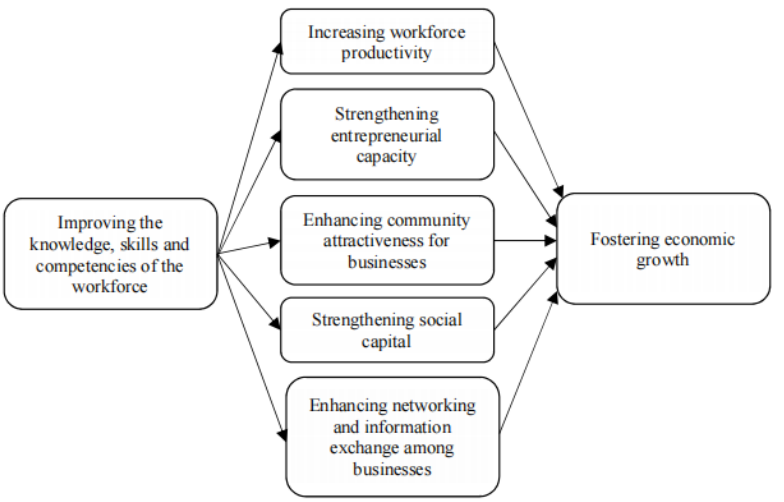

Figure 1: Contribution of human capital to economic growth Source: Adapted from [6]

Modern companies are forced to strive to improve their competitive position by strengthening their technological base and innovation potential. In the process of creating innovations, knowledge plays the most important role. However, in order for innovations to be successfully implemented on the market, appropriate efforts are necessary not only in the field of technology, but also in the field of engineering and marketing, which also imply the application of appropriate knowledge. In order to respond to the demands of changing business conditions, business entities should have appropriate human, financial and material resources, as well as develop cooperation with other business entities. On the other hand, business entities should build their own organizational structure that will enable them to establish an adequate connection between the technological and economic spheres of their business.

As it is not characteristic of technology to develop spontaneously, the process of technology development needs to be managed systematically, strategically planned and long-term oriented. In this sense, the technological strategy represents one of the most important elements of the economic development of every country, and it refers to the long-term exploitation, development and maintenance of the overall knowledge and abilities of the economy and its subjects [2].
Constant changes in the business environment affect the permanent relativization of the position of economic subjects who are forced to constantly adapt to given changes. Observing the technological development in the context of the overall development of the company, the technological development strategy is an integral part of its overall development strategy. Once defined, the technological strategy is not final, but is subject to constant revision in accordance with current changes.

3. THE CONNECTION BETWEEN TECHNOLOGICAL DEVELOPMENT AND MANAGEMENT INNOVATION

Management represents the process of managing business systems with the aim of optimizing their operations, increasing efficiency and profitability. Management can be defined as a process of planning, organizing, hiring, influencing and controlling, which is aimed at the efficient provision, deployment and use of resources in order to achieve a certain goal [2]. Management, in a broader sense, represents deciding on the goals of the organizational system, on the way and means necessary to achieve the given goals, as well as making decisions on the use of the results of the operation of a certain business system. In this sense, management can be viewed from three aspects, namely: management skill, management theory and management structure. Frederick Winslow Taylor is considered to be the founder of scientific management. He believed that management can be developed into a true science, which would be based on exact universal laws, rules and principles, the application and respect of which could improve business [7].
Modern management began to develop and gain importance since the First Industrial Revolution, and over time, its influence on business efficiency has only increased. Management as a scientific discipline went through different stages of development, starting from Frederick Winslow Taylor, the creator of scientific management, to modern theorists, who constituted their management theories in accordance with technical-technological changes and their application in the business process [2].
However, the management methods that are applied today are not always in accordance with changing conditions in the business environment. Until now, the focus of management activities has been directed mainly to improving efficiency, especially productivity, to improving planning, as well as to overcoming the resistance that employees have towards changes. Research shows that in modern conditions this is no longer enough for efficient business. New management methods must be aimed at expanding the awareness, skills and attitudes of employees. In order to achieve this, a multidimensional approach is necessary, which emphasizes the necessity of focusing on all areas, as well as the effort to achieve good results in all areas [4]. Changes should include [8]:

- company,
- organizational structure of the company,
- technology,
- company strategies,
- people (through influence on their behavior, emotions, rational thinking, spiritual development, as well as the process of planning changes in content and employees).

One may ask why innovations in the management process and in the application of management methods are necessary. The answer lies in the fact that the speed of changes in the business environment is increasing, that their unpredictability, mutual conditioning and connection are also increasingly pronounced, as well as their intangibility and the impossibility of seeing the consequences they can have on all aspects of socio-economic life. Innovations in management should be in accordance with the requirements of changing business conditions. Managers must be prepared to solve problems creatively and introduce innovations in management methods. It is also important to point out that managers' responses should be:

- fast,
- directed towards innovation and knowledge-based business development,
- aimed at ensuring a rapid response to environmental challenges.

One of the important characteristics of innovations in modern management is the ability to create adequate strategies for adapting to new changes, which would lead to more efficient execution of operational tasks. In this sense, it is necessary that managers try to include all employees in the process of solving business problems, in order to increase their motivation to perform work tasks, but also to transfer responsibility for the successful performance of given tasks [2]. Therefore, in the future, one of the main tasks of innovation management is to solve the problem of permanent motivation of employees to achieve innovation, greater efficiency and teamwork.

One way to overcome the identified challenges is to enhance innovation activities by applying a process model of knowledge management for innovation, which consists of three phases of the innovation process: *discovery*, *realization* and *nurture* (Figure 2).

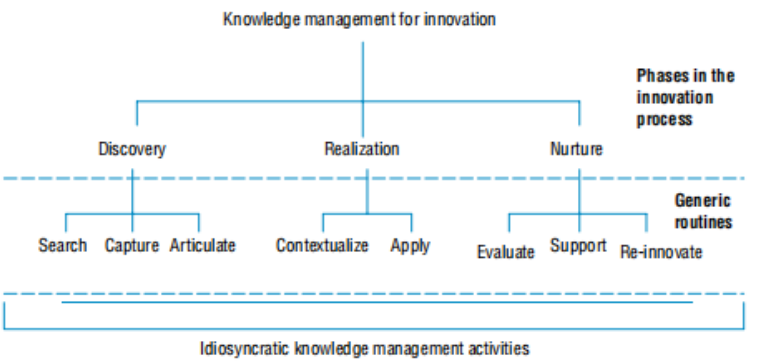

Figure 2: Process model of knowledge management for innovation, Source: [9, 10]

However, the reality is often different. Managers of large companies, due to the complexity of managing substantial assets and a large number of employees, are generally slow in changing their management methods. They are primarily focused on managing within the given circumstances, through cost reduction, process reengineering and incremental changes, while radical management changes are relatively rare in practice.
Research shows that in modern conditions, companies must react faster, be more efficient, flexible and ready to handle discontinuity in business. Precisely because of this, in order for the management methods to correspond to the given requirements, they must be significantly changed. New management methods should contribute to increasing the productivity of business systems that are organized in a new way. It is also important that management innovations contribute to expanding the scope of employees' responsibilities, so that they are more motivated to perform their tasks as efficiently as possible. The essence of management innovation is reflected in the fact that a greater number of employees are encouraged to permanently, when performing of everyday work tasks, provides its maximum. The basis of the comparative advantages of modern companies is represented by:

- passion for doing work,
- creative problem solving and
- the initiative of each individual.

The goal of introducing management innovations is to push the boundaries of existing achievements, both for companies and their employees. In this way, the entire economic recovery and development can be encouraged, because new business conditions imply new managerial and organizational competencies of managers. Companies should improve not only their efficiency, but also their strategic adaptability to changing business conditions. To that end, it is necessary to constantly strengthen innovation in all areas of business, as well as the motivation of employees to achieve optimal results.

4. SPECIFICITIES OF MANAGEMENT INNOVATIONS IN THE TEXTILE INDUSTRY

The textile industry is an economic sector that significantly contributes to the socio-economic development of a large number of national economies. However, due to the specific nature of the production of textile products, the textile industry has numerous harmful effects, such as:

- intensive exploitation of natural resources,
- generation of large amounts of textile waste,
- contribution to the greenhouse effect through the emission of harmful gases,
- water pollution by the release of toxic chemicals,
- pollution caused by microplastics and microfibers, etc.

All of the above indicates the need for radical changes in the operations of textile companies, in order to eliminate or minimize the adverse impacts of their activities. One of the acceptable solutions is certainly the green transition of this economic sector, especially the application of circular economy principles in production and business. The

application of the principles of circular economy in the business of textile companies can contribute to the solution of numerous problems, by reducing environmental damage, increasing the efficiency of resource use, increasing the profitability of business, as well as by improving the quality of life. The implementation of the principles of circularity in the textile industry would contribute to increasing the long-term sustainability of its business companies, since it would enable the production of high-quality products, while extending their lifespan and increasing their value.

Numerous studies point to the fact that the application of the circular economy in business can have numerous positive effects, the most important of which are economic, social and ecological. The most significant *economic effects* are reflected in lowering costs, increasing profits, increasing employment, as well as in the continuous growth and development of the national economy. The most important *social effects* that can be achieved in this way are, first of all, greater usefulness of products for consumers, production of better quality and healthier clothing, improvement of working conditions and earnings of employees, as well as an increase in living standards and more adequate care for the health of the population. The *ecological effects* achieved through the implementation of the circular economy refer to the reduction of environmental pollution, reduction of energy consumption, reduced use of harmful substances in production, etc.

The practical implementation of circularity in the operations of any business entity, however, implies significant changes in the approach and business philosophy, as well as the introduction of new business models. All of this requires the application of new management methods and presents significant challenges for the company's management. In this sense, management innovations in the future development of the textile industry can be very important. In order to determine the direction in which business management methods should be changed, it is necessary to start from the goals to be achieved in the future business and functioning of the textile industry.

The main goals to be achieved through the application of the circular economy in the textile industry can be summarized as follows:

- increasing product durability,
- increasing the possibility for product reuse and repair,
- reduction and elimination the use of dangerous chemicals in the production process and in textile products themselves,
- more efficient use of resources, primarily raw materials and energy.

These goals, along with the continuous increase in recycled content in products, the application of new technologies for production and recycling and the reduction of greenhouse gases, should contribute to the achievement of the main goal, which is the preservation and improvement of life on Earth. On the other hand, circular business should influence the constant reduction and ultimately the elimination of waste, which would also have a positive impact on the reduction of environmental pollution. However, the application of the principle of circularity in the business of textile companies implies the use of new materials, primarily non-toxic biological ones, instead of the ones used so far (synthetics, chemicals, microplastics and microfibers, dyes, etc.). On the other hand, in order to achieve the reduction and elimination of textile waste, it is necessary to apply

completely new or modified existing technological procedures, which are sometimes unavailable or insufficiently developed. New materials and new technological procedures would facilitate the application of the sharing economy, extending the life cycle of textile products, increasing their reuse, and thus reducing waste. In order to realize all these processes, it is usually necessary to completely change the approach and methods of managing the business of textile companies. It is necessary to motivate management and employees to a different way of thinking and a different value system, to initiate and promote innovation when solving problems and to reward innovative solutions that contribute to the more efficient achievement of planned goals. In order to achieve this, it is necessary to start from management and new approaches to business management.

One of the most significant activities in the process of implementing the circular economy is waste recycling, which is one of the prerequisites for completing the cycle of sustainable production. Waste recycling involves the implementation of numerous management activities, from planning and organizing to motivating and controlling. It is necessary to manage the process of production and business so that managers and employees are informed, educated, encouraged and rewarded for the application of modern methods of organization, production, quality control, recycling, marketing, so that their application would contribute to a significant reduction in the production of new textiles from original materials, which would also mean a reduction in the amount of water used, the use of toxic chemicals and the consumption of various forms of energy. The production of textile products should be focused on the use of natural fibers, such as cotton and linen, and recycled fibers would form part of the resource pool of the textile or clothing industry. Whether it is post-industrial, pre-consumer or post-consumer textile waste, it is necessary to recycle it and leave it in the further processing cycle [11]. In this way, textile companies should be directed to recycling as a way to implement a circular economy and a way to achieve long-term sustainable development of this sector.

However, managing the recycling of textile waste is a very difficult and complex process. This is precisely the reason why the recycling of textile waste was not carried out to a greater extent before. The main reasons can be economic, then the characteristics and composition of the textile products themselves, the lack of textile material suitable for recycling, the lack of appropriate technologies, the lack of necessary knowledge, information, policies, standards, and inadequate management of the given process [12]. Therefore, the adaptation of management methods to the problems of recycling in the textile industry opens a new issue of introducing adequate innovations in that process. Managers should initiate, encourage and motivate employees to: create such a design of textile products that allows for easy disassembly, the possibility of recycling and the use of as few types of materials as possible, then the construction of an appropriate infrastructure for the efficient collection of textile waste, the application of new technologies for efficient sorting of waste, as well as undertaking adequate activities in order to increase the demand for recycled textiles [13]. The new business models created should enable the development of clothing rental services, then the development and application of a new design of textile products that would enable their reuse and recycling, influencing consumers to buy clothing that, thanks to higher quality, has a longer lifespan,

as well as developing consumer awareness of the benefits of sustainable textile products. The application of the principle of circularity in the textile sector would significantly affect the reduction of the generation of new waste. The responsibility for whether and to what extent modern business methods are represented lies mostly with the management.

In developed countries, the green transition measures of the textile industry have been applied for decades. These measures are based on the necessity of the transition itself, as well as on the necessity of applying new business models that would contribute to increasing the sustainability of this sector. Realization of the process of production of ecological clothing implies appropriate management of all its stages, starting from the creation of design for the environment, procurement of raw materials, production of clothing itself, proper distribution, and up to the consideration of their reverse logistics and waste [14]. According to Walter [15], three innovative trends are predicted to have a primary impact in the textile and clothing industry in the future. These are: digitization, sustainability, circularity and efficiency of resources, processes and the entire business, and new business and consumer models based on the sharing of production resources and final products, servitization, pay-per-use or subscription models.

In new production conditions, it is necessary to apply new management methods. The given management models must be comprehensive and aimed at increasing business efficiency by extending the life of products and closing the material loop in business.

In practice, the difficulties in applying the principle of circularity are influenced by a large number of factors, the most prominent of which are [16]:

- inadequate management methods,
- bad legislation,
- lack of digitization,
- lack of suitable workforce,
- lack of financial resources,
- irrational use of resources,
- market problems,
- difficult to change the way of thinking and value system,
- short-term visions, etc.

The biggest obstacles identified in the literature [17, 18] are:

- technological, financial and economic,
- organizational,
- supply chain,
- institutional,
- consumer-related,
- socio-ecological.

Managing the application of innovative and circular business models in the textile industry is a very complex and difficult process. This is supported by the fact that the lack of financial resources, appropriate technology, infrastructure, necessary knowledge and skills, as well as the absence of strategic planning and the like, can cause the process to be delayed or significantly slowed down. All factors affecting the absence and slowing down of the green transition process can be internal or external in nature.

Internal limiting factors are the high costs of the sustainable business process itself, the lack of awareness of the necessity of creating sustainable innovations, etc., while external factors can be the lack of public support in the field of finance, the underdevelopment of public-private partnerships, the instability of the macroeconomic environment, and the like [19].

In the future development of the textile industry, the focus of management will be on the green and circular transition of this sector. This is particularly important because the application of sustainability principles in the future operations of the textile sector is necessary, but the implementation of such a process is usually a long and arduous. This process is much faster and more efficient in highly developed countries, while less developed countries, due to the lack of their own resources, especially financial, but also technological and infrastructural, face much more serious obstacles, which make the process of green transition much slower and less efficient.

The main focus of the European Commission's new strategy in the field of textile production is increasing the durability of textile products and the possibility of their repair and reusability, as well as increasing the possibility of their recycling, while combating against fast fashion. By applying innovative solutions, it would be possible for the textile industry to be more sustainable, climate neutral, and energy and resource efficient, while respecting human rights and environmental criteria, especially in the sphere of waste generation [20].

Papamichael et al. [16] created a new holistic business model that applies to all stages of the supply chain, and with the implementation of which it is possible to extend the life of the product, especially by using waste as raw material. One of the opportunities for management innovation in the textile industry can be directed towards undertaking appropriate management measures that would result in the improvement of existing products and processes, then towards the application of green operations in production and regeneration processes, reverse logistics, network design and waste management [14].

In order to realize this, it is necessary:

- conduct long-term strategic planning of the development of the textile sector,
- change in the design of the organization of textile entities in accordance with the planned changes,
- motivate employees to accept and implement the planned changes,
- ensure an adequate number and structure of employees who will implement those changes,
- provide adequate control over the implementation of the planned strategy.

All this represents a very complex and demanding task of company management. This complexity is reflected in numerous and complex tasks that need to be fulfilled, such as: application of eco-design of products, improvement of environmental protection, quantification of circularity, as well as transfer of knowledge to employees and customers in the fashion industry. Such innovative management should enable a much faster green transition of the textile industry.

Managing the business of textile companies is very challenging and complex. This is influenced by numerous difficulties faced by these business entities, such as, above all: low

business profitability, irrational and unsustainable use of raw materials, lack of adequate labor force, increased competition from third countries, etc. Since the application of the circular model implies appropriate resources, and above all adequate knowledge, experience and skills, as well as constant research and development work, which are not always available to the required extent, the problem of managing the acquisition, use and distribution of resources is thus more complex. In this sense, management activities should be directed towards:

- strengthening innovation in the field of new production processes and finding new technological solutions,
- development of new digital technologies,
- supporting innovative entrepreneurship and
- provision of adequate infrastructure and logistics for textile waste management.

The main problem faced by management in managing textile companies is how to overcome the problems of the current business, which concern, above all, the generation of waste, environmental pollution, oversized production and consumption, etc., and which make this sector unsustainable in the long term. On the other hand, falling costs, growing demand for textile products and growing consumption make these problems even more complicated, because they cause an excessive growth of clothing production, which is further stimulated by the growth of the world population and the expansion of the middle class, as well as the growth of living standards [11]. Since it is predicted that there will be an increase in the production of the textile industry in the coming years, which according to estimates would amount to about 4% per year until 2030 [21], measures are necessary to radically change something in this area. Consequently, the introduction of adequate management innovations represents one of the very important steps in the future sustainable development of the textile sector.

5. CONCLUSION

Technological development drives increasingly significant, rapid and uncertain changes in economic conditions. In such business conditions, survive only business entities that adequately react to given changes in time and at the appropriate speed. Changed conditions imply the application of changed management methods, as a result of which management innovations in business management are necessary. The textile industry represents one of the sectors in which there are great opportunities for applying management innovations, since it is an economic sector that must undergo a green transition, which implies a completely different business philosophy. As a result, the paper concludes that a change in management methods and business models is necessary in this sector. It is emphasized that managing the application of innovative and circular business models in the textile industry is a very complex and difficult process, due to the lack of financial resources, appropriate technology, infrastructure, necessary knowledge and skills, as well as due to the absence of strategic planning.

It can be concluded that in the future development of the textile industry, the focus of management will be on the green and circular transition of this sector. The application of

the principle of sustainability in the future business of the textile sector is necessary, but the implementation of the given process is usually a long and arduous process. This process is much faster and more efficient in highly developed countries, while in less developed countries, the green transition process is significantly slower and less efficient. The main task of the management when managing the business of textile companies is how to overcome the problems of the current business, which concern, above all, the generation of waste, environmental pollution, oversized production and consumption, etc., and which make this sector unsustainable in the long term. On the other hand, falling costs, growing demand for textile products and growing consumption make these problems even more complicated, as a result of which the introduction of adequate management innovations is one of the very important steps in the future sustainable development of the textile sector.

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SERVICE LEARNING AS A CATALYST FOR SUSTAINABLE FASHION EDUCATION

Review paper
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ABSTRACT: *Integrating service learning (SL) projects into higher education fashion seminars is an effective pedagogical approach that combines academic learning with meaningful community engagement, offering students with transformative real-world experiences. Since gaining prominence in the early 2000s, SL has sought to enrich educational outcomes while addressing social challenges through practical application. This approach deepens students' understanding of theoretical concepts and fosters essential competencies such as creativity, empathy, and social responsibility, which are increasingly important in today's complex global context. In fashion education, SL is often implemented through projects where students design garments for underserved communities, addressing both industry-related challenges and broader societal issues, including sustainability and inclusivity. The growing recognition of SL's educational value has led to its inclusion in curricula at all levels, from primary education to postgraduate studies, promoting sustained collaboration between educational institutions and community partners. This study explores the integration of SL projects into higher education fashion courses, with a particular focus on sustainability within the textile, clothing, and fashion industry. It draws on a review of relevant literature, selected case studies, and an analysis of the potential of SL in fashion education. The findings indicate that well-designed SL projects enhance student engagement, support the development of critical thinking, promote ethical awareness, and contribute to community development. Despite its considerable potential, the implementation of service learning in fashion education faces challenges such as limited resources, time constraints, logistical complexities, the need to maintain academic rigour, and the requirement for meaningful community engagement. Nevertheless, service learning has significant capacity to empower students to become responsible professionals and advocates for positive change within the fashion sector.*

Keywords: *service leaning, fashion education, sustainability, community development.*

SERVISNO UČENJE KAO KATALIZATOR ODRŽIVOG MODNOG OBRAZOVANJA

APSTRAKT: *Integracija projekata servisnog učenja (SU) u visokoškolske modne seminare predstavlja efikasan pedagoški pristup koji povezuje akademsko učenje sa smislenim angažovanjem zajednice, pružajući studentima transformativna iskustva iz realnog okruženja. Od kada je steklo veću prepoznatljivost početkom 2000-ih godina, servisno učenje ima za cilj unapređenje obrazovnih ishoda uz istovremeno suočavanje sa društvenim izazovima kroz praktičnu primenu. Ovakav pristup produbljuje razumevanje teorijskih koncepata kod studenata i podstiče razvoj ključnih kompetencija, kao što su kreativnost, empatija i društvena odgovornost, koje su od sve većeg značaja u savremenom, složenom globalnom kontekstu. U modnom obrazovanju, servisno učenje se često realizuje kroz projekte u okviru kojih studenti dizajniraju odevne predmete za društveno marginalizovane zajednice, čime se istovremeno adresiraju izazovi modne industrije i šira društvena pitanja, uključujući održivost i inkluzivnost. Sve veće prepoznavanje obrazovne vrednosti servisnog učenja dovelo je do njegovog uključivanja u nastavne planove i programe na svim nivoima obrazovanja, od osnovnog do postdiplomskih studija, čime se podstiče dugoročna saradnja između obrazovnih institucija i partnera iz zajednice. Ova studija razmatra integraciju projekata servisnog učenja u visokoškolske studijske programe iz oblasti mode, sa posebnim fokusom na održivost u tekstilnoj, odevnoj i modnoj industriji. Zasniva se na pregledu relevantne literature, odabranim studijama slučaja i analizi potencijala servisnog učenja u modnom obrazovanju. Rezultati ukazuju na to da dobro osmišljeni projekti servisnog učenja povećavaju angažovanost studenata, podstiču razvoj kritičkog mišljenja, unapređuju etičku svest i doprinose razvoju zajednice. Uprkos značajnom potencijalu, primena servisnog učenja u modnom obrazovanju suočava se sa izazovima kao što su ograničeni resursi, vremenska ograničenja, logističke složenosti, potreba za očuvanjem akademske rigoroznosti i zahtev za smislenim uključivanjem zajednice. Ipak, servisno učenje ima značajan kapacitet da osnaži studente da postanu odgovorni profesionalci i zagovornici pozitivnih promena u modnom sektoru.*

Ključne reči: *servisno učenje, modno obrazovanje, održivost, razvoj zajednice.*

1. INTRODUCTION

The term sustainability has become a defining concept since the 1990s, promising balance and continuity in a world often characterised by instability and rapid change. The rise of the sustainability movement is particularly compelling, as it offers a holistic response to environmental challenges by linking nature, culture, values, power relations, and technology. However, sustainability does not represent a single unified approach; instead, it encompasses diverse perspectives and practices shaped by different communities and interests. It operates at multiple levels, from global policymaking and environmental expertise to grassroots initiatives, including social, environmental movements, indigenous knowledge systems, and locally driven efforts to transform communities [1]. According to

the World Commission on Environment and Development, sustainability is defined as „development that meets the needs of the present without compromising the ability of future generations to meet their needs”. The concept has since evolved into the „Triple Bottom Line”, encompassing social, environmental and economic performance [2, 3].
In the textile and clothing sector, sustainability is particularly pressing, as products have environmental impacts at every stage of their lifecycle. In recent years, growing awareness of the fashion industry’s environmental and social consequences has led to an increase in sustainability initiatives [4].
Fashion is a dynamic and ever-evolving concept, yet its fundamental meaning endures. It serves as a form of cultural expression, closely linked to identity, social status, and interpersonal relationships. Although often regarded as transient and superficial, change – an essential attribute of fashion – is not inherently positive or negative; its impact depends on its nature. In contrast, sustainability is based on a long-term perspective. Fashion can involve discarding fully functional garments for symbolic or semiotic reasons, which contributes to significant waste at the end-use stage and therefore appears to conflict with sustainability goals [4].

Figure 1: Discarded knitwear waste resulting from fast fashion and excessive consumerism

From the consumer perspective, awareness of social and environmental issues is increasing. Environmental attitudes significantly influence eco-fashion consumption, and studies indicate that consumers are willing to purchase sustainable fashion products and even pay higher prices, provided quality expectations are met [4]. However, knowledge of sustainability within the fashion sector, although improving, remains limited and is often shaped by popular narratives rather than critical understanding. This reflects and perpetuates the tendency to view fashion as „an immoral, self-indulgent industry… that lacks gravitas and a strong conceptual framework” [5].
For sustainability to become fully embedded in the fashion sector, more comprehensive communication and education are required to develop ecological literacy and an

understanding of the interconnections between natural and human systems. Designers play a crucial role in articulating new visions of sustainable fashion, providing tools, practices, and narratives that can foster collective change. Such communication may extend beyond traditional visual forms and classroom settings, taking shape through experimental practices such as prototype business models, artefacts, services, workshops, and participatory initiatives [6].

In this context, integrating innovative teaching methods into fashion education offers significant potential. By reshaping design thinking and conceptual approaches among emerging designers, these methods may help transform production practices and, indirectly, consumers' attitudes towards sustainability. New teaching methods in sustainable fashion design at all levels of education aim to pass on knowledge and cultivate responsible, informed consumers within the fashion industry, reflecting a growing recognition of the urgent need for sustainability in global textile practices.

2. INNOVATIVE APPROACHES TO TEACHING SUSTAINABILITY CONCEPTS IN FASHION

Innovative teaching methods in fashion design education increasingly focus on experiential, participatory, and research-led approaches that prioritise sustainability. Classroom and studio-based teaching is complemented by interdisciplinary collaboration, design thinking, and practice-based experimentation, enabling students to critically engage with the environmental and social implications of textile and fashion design decisions. Methods such as material and process exploration and evaluation, universal design, adaptive design, design for longevity, upcycling, zero-waste pattern cutting, and concepts such as product-service systems, including rental and repair, encourage students to reconsider the sustainability of conventional materials, production processes, and consumption models [5, 7, 8].

Project-based engagement with real-world stakeholders, such as local communities, industry partners, non-profit organisations, and circular economy initiatives, can foster a reflective understanding of sustainability as both a design challenge and a cultural and social engagement practice. Such pedagogical approaches promote technical competence, ethical awareness, and critical thinking, equipping emerging designers to articulate alternative visions of fashion.

Contemporary fashion education increasingly emphasises communication at all levels as a key design outcome, enabling knowledge transfer from designers to consumers. Through methods such as co-design, interactive workshops, collaborative projects, and digital platforms, students are trained to engage consumers as active participants in sustainable practices rather than passive recipients of products [6, 7].

By developing textile and clothing products, services, and narratives that reveal the lifecycle, value, and meaning of textiles and clothing, designers can influence consumer attitudes and behaviours. In this way, novel teaching approaches help form a new generation of designers who create sustainable fashion and communicate its significance effectively, thereby fostering more informed and responsible consumption patterns.

As environmental awareness grows, educational institutions are innovating their curricula by integrating principles of sustainable development, ethical design, and responsible production. Controversies surrounding sustainable fashion education often focus on the challenge of reconciling economic viability with sustainable practices. Many educational frameworks struggle to shift entrenched industry mindsets, where sustainability is sometimes regarded as a marketing tool rather than a foundational principle. This highlights the need for genuine commitment to sustainability within both educational settings and the fashion industry, preparing students to confront the status quo and drive meaningful change. Educators can play an activist role, although the fashion education system can be challenging as a medium for large-scale change. As educators continue to adapt curricula to reflect these dynamics, the potential for sustainable fashion education to shape a more ethical and environmentally responsible industry becomes increasingly clear [9-11].

Educational institutions and teachers must act as agents of change and are crucial in initiating transformation and implementing new teaching methods aligned with contemporary developments.

3. SERVICE LEARNING AS A CONCEPT SUPPORTING SOCIETAL WELL - BEING IN SUSTAINABILITY

3.1. Sevice-learning approach

Service learning is an innovative and impactful educational approach that has gained considerable momentum in recent years. Serving as a bridge between academic learning and community service, service learning enables students to translate their theoretical knowledge to practical solutions for real-world problems, while simultaneously developing their skills and understanding. The multi-dimensional benefits of service learning are extensive, significantly contributing to students, teachers, communities, and policy-makers in education [12].

Although the concept of service learning has historical roots, tracing back to John Dewey’s philosophy of experiential learning, it was not until the 1980s that it was defined as a distinct pedagogical approach. Initially, it focused primarily on volunteering and community service, emphasising service over academic learning. This approach often took place in informal settings, such as campus organisations or community clubs, where students participated in service activities without structured educational objectives. Today, service learning is embraced by many educational institutions worldwide, shaping the curricula of thousands of schools, colleges, and universities [12, 13].

3.2. Benefits and predicamenst of sevice-learning

There are many proven benefits of incorporating service learning into the curriculum for all participants.

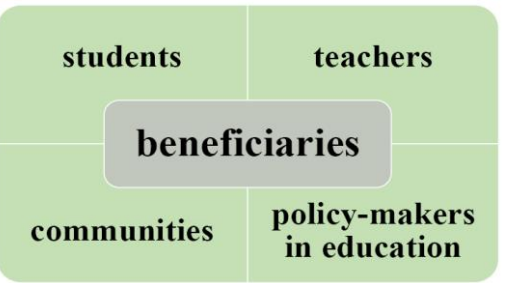

Figure 2: Key beneficiaries of service-learning integration

Students benefit through:
- improved communication and leadership skills, increased self-awareness, and greater knowledge of community needs and local or global issues,
- stronger connections between academic subjects through an interdisciplinary approach,
- enhanced problem-solving ability and real-life skills,
- strengthened class group communication,
- increased empathy and responsibility,
- deeper critical thinking skills [14].

Teachers are provided with:
- an innovative pedagogical approach that aligns academic learning with real-world applications, making the learning process more engaging and relevant,
- a collaborative learning environment that enhances teacher-student relationships and creates a more dynamic, inclusive classroom,
- professional development opportunities through the acquisition of new skills and methodologies,
- a sense of fulfilment from contributing to societal change [12].

Communities receive:
- support from students, who bring fresh perspectives, unique skills, and innovative knowledge,
- recognition of community needs, including education, health, environmental conservation, and social justice [12].

Policy-makers in education benefit from:
- the effectiveness of experiential learning, which incorporates best practices into curricula,
- the achievement of educational policy goals, such as improving student outcomes, fostering civic responsibility, and promoting community engagement,
- partnerships between educational institutions and community organisations, aligning school objectives with community needs promoting holistic societal development [12].

While implementing the service-learning concept at all levels of education offers substantial benefits for students, teachers, the community, and policy-makers, successful integration requires addressing the associated predicaments and challenges. Unclear

definitions of roles and expectations among students, teachers, and community partners can result in mismatches between intended and actual outcomes.
The greatest obstacles to incorporating service into coursework are:
- time pressures and inflexible teaching loads,
- resistance to curricular changes, including the obligation to complement existing curriculum requirements while meeting educational goals,
- lack of support for educational institutions at the institutional level,
- lack of resources such as budget and funding, insufficient teaching materials, and staff shortages [15].

Despite increasing recognition of the service-learning approach across disciplines, its application in sustainable textile, clothing, and fashion education remains underexplored. Most existing research focuses on fields such as business, engineering, and health sciences, overlooking the unique combination of creative, technical, cultural, and ethical dimensions in fashion education. This gap is particularly significant given the industry's urgent sustainability and social responsibility challenges.

4. SERVICE LEARNING IN TEXTILES, CLOTHING AND FASHION: CASE STUDIES

4.1. African Happy Pants™ product range expansion

The service-learning project conducted by Strydom and Tslepis [16] at the University of Pretoria centred on a partnership between a university department and a social entrepreneur to address real-world product development needs in the apparel sector. The main objective was to expand and improve an existing clothing product range, African Happy Pants™, while exposing final-year clothing management students to the realities of apparel product development. Through this collaboration, students applied the design process to develop new prototypes, bridging a skills gap in the community partner organisation, which lacked design expertise. The project content was more technical in nature than related to sustainable fashion.
The outcomes demonstrated clear mutual benefits. Students provided tangible design solutions that enhanced the partner’s product offerings, while gaining hands-on experience with real clients and production constraints. Reported benefits for students included the development of higher-order cognitive skills such as critical thinking, design, analysis, synthesis, and evaluation, as well as the ability to apply theoretical and practical knowledge in authentic contexts. Students also acquired valuable work-related competencies and practical experience, highlighting how service-learning can strengthen professional readiness and deepen understanding through real-world engagement.

4.2 Reusable food bags

Hwang et al. [17] conducted a collaborative service-learning project within fashion and textile education, with the primary objective of understanding how such experiences influence student learning. Specifically, the study aimed to:
- explore students’ learning experiences in a collaborative service-learning context,
- analyse how factors such as service-learning engagement, civic responsibility, and

enjoyment contribute to students' academic development, and
- propose a broader framework for integrating social responsibility initiatives into multi-course fashion curricula.

As part of the project, fashion students created reusable food bags for a local community action food bank. In the textiles course, they learned about various textile materials, their properties, end uses, and care methods. Drawing on this knowledge, they sourced post-consumer textile waste containing fabrics durable enough to hold the weight of cans and dry goods. Textiles sourced from family, friends, charity shops, and past student projects included drapes, tablecloths, trousers, and fabric scraps. The project brought students into collaboration with community partners, combining academic content with real-world problem-solving and social engagement. The project content was sustainable, but it was not related to fashion products.

Students' academic development was positively influenced not only by knowledge acquisition but also by affective factors such as enjoyment, a sense of civic responsibility, and engagement with the service experience. Reported benefits for students included enhanced understanding of course material, increased motivation, and the development of social awareness and responsibility. Such projects can strengthen students' holistic learning by connecting disciplinary knowledge with meaningful community interaction, while also providing a structured approach to embedding social responsibility in fashion education.

4.3. Upcycling fashion for seniors

Chae [18] reported on a service-learning project that integrated a semester-long community engagement experience into a capstone fashion design course. The main objectives were:
- to collect qualitative data on the clothing needs of senior citizens through direct interaction,
- to apply and test the design process using the Functional–Expressive–Aesthetic (FEA) framework, and
- to develop upcycled garment prototypes that are functional and appealing while addressing actual user needs.

Through one-to-one collaboration with seniors living in a community housing facility, students participated in a real-world design context that emphasised empathy, sustainability through upcycling, and user-centred design practices. The project content was strongly sustainability-oriented, but focused more on functionality than fashion.

The project outcomes demonstrate mutual benefits for all participants. Students and seniors worked together positively, resulting in clothing solutions that better reflected the needs and preferences of older adults while providing affordable, upcycled garments. The project effectively linked academic learning with community impact, strengthened relationships between the university and the local community, and generated tangible design outputs.

For students, the experience enhanced their ability to work with real clients, particularly those outside their usual interests or comfort zones, and helped them articulate and apply their design knowledge in practical settings. Reported benefits for students include improved communication with clients, a deeper understanding of user-centred design, increased confidence, and expanded professional and interpersonal skills through hands-

on, collaborative experience.

4.4. Sustainable fashion walk in Ljubljana

The Erasmus+ TexUnite project [19] promotes the key competences required to achieve sustainability goals by introducing service learning into textile, clothing, and fashion education through project-based seminars. The project develops an online educational seminar for higher education, featuring digitally enhanced teaching and learning formats for implementing sustainability-oriented service learning project seminars with external partners. The virtual exchange method facilitates intercultural exchange among the six European partner universities.

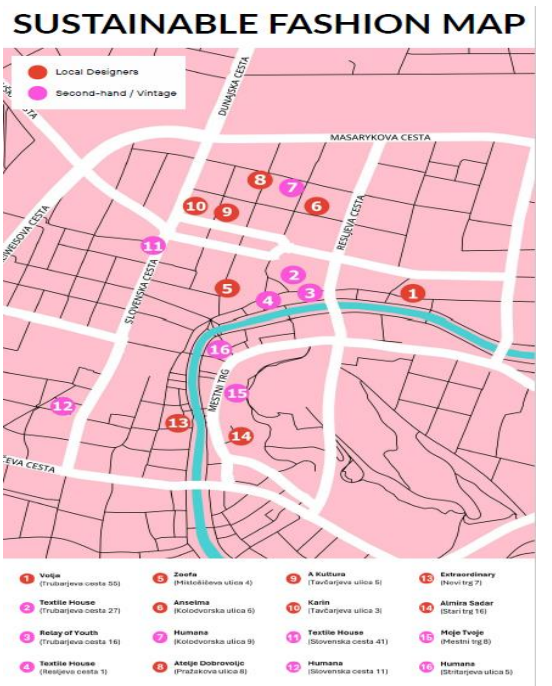

Figure 3: Map of the Sustainable Fashion Walk in the Ljubljana guide

One of the service learning projects, conducted by the University of Ljubljana, focused on providing sustainable fashion products. The goals of the project were:

- educating students about the principles of sustainability, including the key objectives of the EU Textile Strategy for Sustainable and Circular Textiles,
- introducing students to the latest sustainable clothing technologies and zero-waste practices,
- promoting a mindset that values sustainability as an integral part of the fashion and textile industry, and encouraging students to prioritise environmental and ethical

considerations in their future careers,
- creating a map of sustainable fashion in Ljubljana with shopping tips that promote sustainability, and sharing the map on social networks to promote the values of sustainable behaviour in relation to fashion.

A third - year Textile and Fashion Design Programme student from the Clothing Technology Support course took part in the project.

5. CONCLUSIONS

Service learning is a powerful pedagogical innovation in textile, clothing, and fashion education, addressing the need to prepare students for professional practice while fostering civic responsibility and social consciousness. Evidence from reported case studies shows that well-designed service learning projects enhance technical competencies, interpersonal skills, and ethical awareness, while providing tangible benefits to community partners. Success depends on reciprocity, structured reflection, institutional support, and comprehensive assessment.

Integrating sustainability into textile, clothing, and fashion education is essential for preparing future designers to address the industry's pressing environmental challenges. Embedding sustainability practices into the curriculum from an early stage fosters lasting habits and informed consumer choices among students.

As the fashion industry faces urgent sustainability and social responsibility challenges, service learning offers a pathway to educate change agents with both professional expertise and a commitment to community benefit. Future research should examine longitudinal outcomes, the comparative effectiveness of different implementation models, and strategies for scaling service learning across fashion curricula.

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TexUnite

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INFLUENCE OF TACIT KNOWLEDGE AND USER BEHAVIOUR ON DIGITAL EFFICIENCY OF AUTOMATED ORGANIZATIONAL SUPPORT FUNCTIONS IN TEXTILE INDUSTRY

Review paper
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ABSTRACT: *This paper investigates how tacit knowledge and user behavior (employees) influence the effectiveness of automation and AI-driven tools in organizational support functions. Drawing on Knowledge Management and Socio-Technical Systems theory, the study adopts a human-centric perspective aligned with Industry 5.0. Evidence from textile manufacturing and supply chain environments, supported by insights from prior research on tacit knowledge in automated business environments, shows that digital efficiency is shaped not only by technological capabilities but also by how employees interpret, adapt, and at times circumvent formalized systems in their daily work. In practice, system complexity and ingrained routines often lead workers and managers to rely on familiar "legacy" approaches or informal workarounds, even when advanced digital solutions are available. While these behaviors may enhance short-term efficiency, they can reduce data reliability, limit process visibility, and constrain organizational learning. The findings emphasize that, regardless of the level of automation, the end user ultimately determines system effectiveness. The paper concludes that sustainable digital transformation requires balancing technological innovation with the preservation of human expertise and collaborative practices.*

Keywords: *tacit knowledge, user behaviour, process automation efficiency, Industry 5.0, human-centric approach.*

UTICAJ TACITNOG ZNANJA I PONAŠANJA KORISNIKA NA DIGITALNU EFIKASNOST AUTOMATIZOVANIH ORGANIZACIONIH FUNKCIJA PODRŠKE U TEKSTILNOJ INDUSTRIJI

APSTRAKT: *Ovaj rad ispituje kako tacitno znanje i ponašanje korisnika (zaposlenih), utiču na efikasnost automatizovanih i veštačkom inteligecijom pokrenutih alata u funkcijama organizacione podrške. Oslanjajući se na teoriju upravljanja znanjem i socio-*

tehničkih sistema, studija usvaja perspektivu usmerenu na ljude, usklađenu sa principima Industrije 5.0. Rezultati iz tekstilne proizvodnje i lanca snabdevanja, potkrepljeni uvidom u prethodna istraživanja o implicitnom znanju u automatizovanim poslovnim okruženjima, pokazuju da digitalnu efikasnost oblikuju ne samo tehnološke mogućnosti, već i način na koji zaposleni tumače, prilagođavaju, a ponekad i zaobilaze formalizovane sisteme u svakodnevnom radu. U praksi, složenost sistema i ukorenjene rutine često navode radnike i menadžere da se oslanjaju na poznate "naseđene" pristupe ili neformalna zaobilazna rešenja, čak i kada su im na raspolaganju napredna digitalna rešenja. Iako ova ponašanja mogu poboljšati kratkoročnu efikasnost, ona mogu umanjiti pouzdanost podataka, ograničiti vidljivost procesa i otežati organizaciono učenje. Nalazi naglašavaju da, bez obzira na nivo automatizacije, krajnji korisnik u krajnjem odrešuje efikasnost sistema. Rad zaključuje da održiva digitalna transformacija zahteva uravnoteženje tehnoloških inovacija sa očuvanjem ljudske ekspertize i kolaborativnih praksi.

Ključne reči: *tacitno znanje, ponašanje korisnika, efikasnost automatizacije procesa, Industrija 5.0, pristup usmeren ka čoveku.*

1. INTRODUCTION

Automation and digital technologies are transforming how organizations produce, manage, and deliver work [1,2]. Digital transformation is seen as a main strategic goal accross different industries, as well as textile industry. It is driven by the integration of artificial intelligence (AI), machine learning (ML), enterprise resource planning (ERP) systems, robotic process automation (RPA), digital twins, and advanced analytics. These technologies are increasingly implemented not only in production environments but also in organizational support functions such as procurement, accounting, payroll, contract administration, supply-chain coordination, and risk management [3,4]. Research on AI adoption in textile environments increasingly highlights the importance of preserving and transferring tacit knowledge, particularly as organizations face workforce transitions, increasing automation, and growing complexity of digital systems [5,6]. In support functions such as accounting, payroll, finance, and risk management, ERP, RPA, and AI tools have replaced many manual tasks [7,8]. While these systems deliver speed and consistency, they remain dependent on human users who provide data, interpret outputs, and maintain process discipline [9,10]. As digitalization expands, organizations risk losing tacit knowledge embedded in experience and social interaction [11,12]. Such knowledge enables employees to anticipate errors and adapt to exceptions [13,14]. When it erodes, digital systems become increasingly fragile under disruption [15,16]. Moreover, workload pressure and organizational constraints encourage procedural shortcuts that may undermine data quality and system integrity [17,18,19].
This study therefore combines Knowledge Management and Socio-Technical Systems perspectives within the Industry 5.0 framework to examine how user behaviour and tacit

knowledge jointly shape digital efficiency [20,21,22]. (Trist & Bamforth, 1951; Bostrom & Heinen, 1977; European Commission, 2021). Through the literature research.

2. LITERATURE REVIEW

2.1. Tacit Knowledge Dimension in Digital Work

Automation has become central to contemporary organizational life, particularly in administrative and support functions such as accounting, payroll, and financial operations. Yet, despite technological sophistication, the performance of these systems continues to depend on human understanding, experience, and judgment. Within the field of Knowledge Management (KM), this human contribution is captured by the concept of tacit knowledge—the unspoken, experience-based understanding that enables people to interpret data, solve problems, and adapt to exceptions [11,12]. Tacit knowledge differs from explicit knowledge, which can be codified and stored in manuals or systems. It is situated, relational, and often invisible to formal documentation processes [23]. When organizations automate procedures, they typically convert parts of tacit knowledge into explicit, rule-based forms. However, this process also generates losses: employees begin to “click through” systems without fully understanding the underlying logic of their work [24]. In digital support functions systems, for example, the capacity to troubleshoot errors or interpret exceptions depends on retaining tacit understanding of data flows and dependencies. When this erodes, automation may deliver accuracy under normal conditions but vulnerability under disruption. The human challenge in automation, therefore, is not only the loss of tacit knowledge but also the need to reproduce it through learning, mentoring, and documentation. The reproduction of tacit knowledge allows new employees to grasp not just what to do, but why procedures matter. Conversely, when work becomes fragmented by digital interfaces, the opportunity for reflective learning diminishes, and organizational memory weakens [25].

2.2. User Behaviour Dimension

The implementation of AI-driven systems influences employee behaviour by reshaping workplace dynamics, increasing operational efficiency while simultaneously affecting autonomy, decision-making practices, and user interaction with digital processes [26].
Organizational Behavioral studies of work show that employees frequently adjust formal procedures to meet real operational demands. This is particularly visible in environments of high workload, time pressure, and limited control over system performance. According to [16,17], such deviations are not necessarily negligent; they are rational adaptations to system constraints. People take shortcuts to achieve results, even when these shortcuts undermine reliability. Within digital systems, this manifests as rational non-compliance: users knowingly bypass certain steps because following them would slow performance or because the system itself is cumbersome. For example, employees may skip “lessons learned” fields in ticketing systems, reuse old data entries, or rely on email rather than integrated communication channels. These behaviors create what [15] described as “latent conditions” for failure—errors embedded in the system’s everyday operation.

From a knowledge-management perspective, these adaptations also disrupt knowledge flows. Every skipped documentation step represents a lost opportunity to capture experiential insight. Over time, the organization's collective memory weakens, and inefficiencies repeat. The popular maxim "bad data in, bad data out" illustrates how behavioral drift undermines both data quality and system credibility.
Recent workplace research links these behaviors to structural and cultural factors: increasing workload, understaffing, and shifting motivational patterns [27]. Employees often feel pressured to prioritize speed over reflection and perceive knowledge-sharing as an optional or unrewarded task.

2.3. Digital Efficiency of Automated Organizational Support Functions in Textile Industry

Digital transformation has become a strategic priority within the textile industry as organizations seek to improve operational performance, supply-chain responsiveness, sustainability, and competitiveness. While early digitalization efforts primarily focused on manufacturing technologies and production automation, recent developments increasingly extend into organizational support functions. The concept of digital efficiency refers to the ability of digital technologies to improve organizational performance through faster information processing, enhanced transparency, reduced operational costs, and improved process integration. In textile organizations, digital efficiency is particularly important due to the complexity of supply chains, high product variability, global sourcing networks, and increasing customer expectations regarding speed, customization, and sustainability [28]. Several textile-industry case studies highlight the operational benefits of digitalization in support processes. Nafz et al. [29] emphasize that digital transformation enables the integration of previously fragmented organizational activities, facilitating data exchange between production planning, procurement, inventory control, and administrative functions. Similarly, Berardi [30] found that digitalization of business-to-business processes in Italian textile companies improved communication efficiency, reduced transactional complexity, and enhanced collaboration across supply-chain actors. These findings suggest that digital efficiency extends beyond technological infrastructure and depends on the organization's ability to connect information flows across both operational and administrative domains. The implementation of data-driven business-process management systems allows organizations to monitor performance indicators in real time and identify operational bottlenecks more effectively. A case study conducted within a Peruvian textile manufacturing company showed that integrating lean-management practices with digital process modelling increased production efficiency from 79% to 86%, improved operational agility, and strengthened decision-making capabilities through real-time performance monitoring [31]. From an Industry 5.0 perspective, digital efficiency should therefore be understood as a dynamic balance between automation, organizational knowledge, and human behaviour. Advanced technologies enable faster processing and improved operational control, but long-term efficiency depends on employees' ability to interpret information, reproduce tacit knowledge, maintain process discipline, and support organizational learning. As textile organizations continue adopting AI-driven support

systems, preserving this human dimension becomes increasingly important for achieving resilient, transparent, and sustainable digital transformation [22,31].

2.4. Influence of Tacit Knowledge and User Behaviour on Digital Efficiency in Textile Industry

One of the most significant findings emerging from recent textile-sector research is that tacit knowledge remains essential even in highly digitalized environments. Chanyanut and Sangnak [32], examining AI-driven knowledge capture in the Thai textile heritage industry, identified strong concerns regarding the loss of experiential expertise caused by aging workforces and weakened intergenerational knowledge transfer. Their study revealed that employees and artisans demonstrated significantly greater acceptance of AI systems when technology was perceived as supporting knowledge preservation rather than replacing human expertise. The authors describe AI as an “epistemic partner” that enables the capture and transmission of tacit knowledge while maintaining human agency within organizational processes. This finding suggests that user behaviour toward AI systems is strongly influenced by whether employees perceive automation as complementary or threatening to their professional knowledge and identity.

A similar conclusion is presented by Baytar, Yang, and Maher [33], who investigated the role of tacit knowledge in apparel product development and explainable artificial intelligence (XAI). Their research argues that many apparel-development decisions rely heavily on experiential judgement, intuition, pattern interpretation, and contextual decision-making that are rarely documented in formal systems. The authors emphasize that successful digitalization and AI implementation require organizations to first identify, externalize, and understand tacit knowledge before it can be effectively incorporated into explainable AI models. They further argue that the inability to decipher tacit knowledge creates barriers to AI adoption because users may distrust or reject automated recommendations that fail to reflect practical expertise accumulated through experience.

Research on tacit knowledge modelling in industrial environments provides additional evidence supporting the importance of human expertise within automated systems. Kipper et al. [34] demonstrate that tacit knowledge significantly contributes to process optimization, anomaly detection, problem-solving, and decision quality. Their findings indicate that industrial systems perform more effectively when expert knowledge is systematically captured and translated into decision-support mechanisms. However, the study also emphasizes that many contextual elements of tacit knowledge remain difficult to formalize because they depend on experience, judgement, and situational interpretation. As a result, automated systems continue to require active human involvement to maintain performance under changing operational conditions.

The relationship between user behaviour and digital-system performance is particularly relevant within textile-industry environments characterized by complex workflows, high product variability, and continuous adaptation requirements. Research presented within the Contemporary Trends and Innovations in the Textile Industry conference proceedings repeatedly highlights the importance of human expertise in process optimization, quality control, and production management. Studies examining textile-process improvement,

quality management, and business-process development emphasize that organizational performance depends not only on technological infrastructure but also on employees' ability to correctly apply procedures, interpret process information, and adapt operational activities to specific production conditions [35,36].

Employees frequently rely on practical experience when making decisions. If AI-generated recommendations are not transparent or understandable, users may bypass system outputs, rely on informal knowledge-sharing practices, or revert to traditional decision-making methods. This behavioural response reduces the effectiveness of automation and limits the organization's ability to achieve consistent digital-process execution. Similar findings from explainable AI research suggest that user trust, transparency, and understandability directly influence system usage behaviour and technology acceptance [37].

Recent research further highlights that organizations face increasing risks associated with tacit knowledge erosion. As experienced employees retire or transition to new roles, valuable operational knowledge may disappear if organizations fail to implement mechanisms for knowledge capture and transfer. Fenoglio et al. [38] emphasize that many digital transformation initiatives focus primarily on technological implementation while neglecting the systematic incorporation of experiential knowledge into ERP systems and automated workflows. Consequently, organizations may achieve short-term efficiency gains while simultaneously reducing long-term organizational resilience and adaptability.

3. CONCLUSION

Automation does not eliminate the need for human knowledge, it redefines it. The study of digital transformation in support functions such as accounting, payroll, risk management, and contract administration reveal that the effectiveness of automated systems depends on how employees reproduce or disrupt tacit knowledge during their everyday interactions with technology. Digital tools may accelerate processing, but human insight sustains meaning, accuracy, and reliability. The reviewed literature indicates that digital efficiency within AI-supported textile-industry environments emerges from the interaction between technological capability, tacit knowledge, and user behaviour. Automated systems improve information processing, process standardization, and operational visibility; however, their effectiveness remains dependent on employees' willingness to engage with technology, trust automated outputs, reproduce organizational knowledge, and maintain process discipline. User behaviour influences data quality, knowledge continuity, system reliability, and organizational learning, while tacit knowledge provides the contextual understanding necessary for managing exceptions, uncertainty, and operational disruptions [32,33,34].

These findings strongly support the Industry 5.0 perspective, which views human expertise as a strategic resource rather than an obstacle to automation. Within textile-industry support functions and production environments, sustainable digital transformation therefore requires not only technological investment but also mechanisms for preserving tacit knowledge, strengthening organizational learning, and encouraging responsible system usage. AI systems can enhance organizational performance, but long-term digital

efficiency depends on maintaining the human knowledge and behavioural capabilities that enable technology to function effectively in complex real-world environments. Further research will be focused on gathering and analysing pracal evidence of impact of tacit knowledge and user behaviour on digital efficiency in support processes.

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APPLICATION OF ARTIFICIAL INTELLIGENCE IN SUSTAINABLE PRODUCTION IN THE FASHION INDUSTRY

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ABSTRACT: *In conditions of increasing demands for sustainability and efficiency, the fashion industry is turning to digital and intelligent technologies. In this work, the focus is on the application of artificial intelligence in the optimization of production processes and the development of sustainable production models. Clo3D software is seen as a key platform for implementing AI (artificial intelligence) solutions through digital prototypes and simulations. The analysis indicates that the combination of AI (artificial intelligence) and 3D simulation significantly contributes to reducing waste, optimizing resources and improving decision-making in design and production.*

Keywords: *artificial intelligence, sustainable fashion, digital production, optimization.*

PRIMENA VEŠTAČKE INTELIGENCIJE U ODRŽIVOJ PROIZVODNJI U MODNOJ INDUSTRIJI

APSTRAKT: *U uslovima sve većih zahteva za održivošću i efikasnošću, modna industrija se okreće digitalnim i inteligentnim tehnologijama. U ovom radu fokus je primena veštačke inteligencije u optimizaciji proizvodnih procesa i razvoju održivih modela proizvodnje. Clo3D softver se posmatra kao ključna platforma za implementaciju AI (veštačke inteligencije) rešenja kroz digitalne prototipove i simulacije. Analiza ukazuje da kombinacija AI (veštačke inteligencije) i 3D simulacije značajno doprinosi smanjenju otpada, optimizaciji resursa i unapređenju donošenja odluka u dizajnu i proizvodnji.*

Ključne reči: *veštačka inteligencija, održiva moda, digitalna proizvodnja, optimizacija.*

1. INTRODUCTION

The global textile and fashion industry represents one of the most powerful economic drivers in the modern world, with a market value exceeding $1.2 billion and a clear projection of growth to over $1.5 billion, while simultaneously employing tens of millions of workers along global and deeply intertwined supply chains. However, this permanent economic contribution and expansion has been accompanied by an unsustainably high,

destructive ecological and social footprint. For decades, the traditional fashion sector has been operating according to the rigid and linear economic principle "take-make-use-dispose", which leads to the uncontrolled exploitation of natural resources. This linear pattern results in the annual consumption of enormous amounts of clean water and fossil fuels, while at the same time generating toxic waste, liquid effluents saturated with heavy metals and countless amounts of solid textile waste that most often end up in overcrowded landfills or are incinerated without energy efficiency. The emergence of the phenomenon of fast fashion (Fast Fashion) has drastically accelerated this destructive cycle, dramatically shortening the lifespan of clothing items and creating systemic hyperproduction that far exceeds the real needs of the global market. According to the latest environmental studies, it is estimated that the fashion industry is responsible for as much as 8 to 10% of the total global greenhouse gas emissions, which puts it at the very top of the global environmental polluters [4].

Faced with increasing, coordinated pressure from international regulatory bodies, environmental organizations and conscious consumer groups, business entities in the fashion sector are forced to implement a radical and comprehensive transformation of their traditional production and logistics models. The transition to sustainable business and a clean circular economy imperatively implies extending the life of the products themselves, maximizing the efficiency of using raw materials, eliminating harmful chemical substances and closing the material loop through the processes of upcycling and advanced recycling. In order to achieve these ambitious goals in practice, it is necessary to implement new methodologies that analyze and optimize the impact of a product on the environment throughout its entire life cycle, from cradle to grave (LCA - Life Cycle Assessment), focusing on reducing the carbon and water footprint [3].

In this complex technological and environmental context, digitization, advanced three-dimensional (3D) simulations and systems based on artificial intelligence (AI) are recognized as the primary and most effective drivers of the systemic transformation of the fashion industry. Artificial intelligence enables the processing of mass data (Big Data), prediction of market demand with a high degree of accuracy and making automated, optimized decisions in real time along the entire vertical value chain. The aim of this paper is to shed new light on the modalities and mechanisms by which artificial intelligence can transform the fashion sector from a linear polluter into a sustainable, circular and fully transparent ecosystem through a detailed scientific analysis of modern software tools for virtual modeling, such as the Clo3D platform, and advanced regulatory-technological mechanisms, such as the Digital Product Passport (DPP).

2. SUSTAINABILITY, CIRCULAR ECONOMY AND ESG STANDARDS

The transition from a linear to a circular economy in the fashion and textile sector is not only a technical issue, but requires a deep and radical change in the corporate paradigm, as well as the widespread adoption of rigorous environmental, social and governance (ESG - Environmental, Social, Governance) standards. Sustainability strategies can no longer rest on superficial and partial solutions; companies today must have an exact, empirically

supported and transparent insight into the complete life cycle of a garment, from the extraction and processing of primary raw materials, through industrial production and distribution logistics, all the way to the stage of consumption and final waste management at the end of life (End-of-Life). Traditional approaches often suffer from a lack of standardization and transparency, which opens up space for manipulative marketing, while the integration of holistic ESG frameworks and environmental accounting allows businesses to accurately quantify and monitor their environmental impacts [2].

Circular economy models within the fashion industry stimulate and open completely new, environmentally neutral and economically profitable business opportunities. These opportunities are primarily related to eco-design, systems of organized repair (repair), platforms for reuse (reuse) and the development of new technologies for mechanical and chemical recycling of high-grade textile fibers. With the introduction of mandatory instruments of due diligence in terms of human rights, working conditions in textile factories and rigorous environmental procedures against pollution, the formation of transparent ESG reports becomes a legal obligation for all economic entities that wish to operate in the single market of the European Union.

In establishing this new framework, the technological solutions of the fourth industrial revolution (Industry 4.0) provide the necessary digital and hardware infrastructure. Through the networking of IoT (Internet of Things) sensors, blockchain technology and advanced AI analytics, textile companies gain the ability to generate accurate, immutable and instantly available data on the consumption of electricity, resources and raw materials in each individual production facility [9]. In this way, artificial intelligence serves as a key validation mechanism that enables a radical transition from declarative and often false sustainability (greenwashing) to scientifically based, measurable and verifiable business sustainability.

3. ARTIFICIAL INTELLIGENCE AND 3D SIMULATIONS IN DESIGN AND PRODUCTION OPTIMIZATION

One of the primary and materially most pronounced sources of textile waste and financial losses in the traditional chain of the fashion industry lies in the early stages of prototyping and development of new garments. In the conventional industry model, design teams are forced to create dozens of physical garment samples that are then shipped across oceans for management and client approval, often going through numerous time-consuming iterations of fit corrections, texture changes, and color shade adjustments. This process consumes hundreds of thousands of kilometers of quality fabric before mass production can even begin, generating high transport emissions and increasing time-to-market. The implementation of artificial intelligence in synergy with software solutions for advanced 3D simulation, such as the Clo3D platform, fundamentally transforms this inefficient and environmentally unacceptable process.

3.1. The role of the Clo3D platform and AI algorithms

The Clo3D software platform is the leading industry standard for creating high-precision (Digital Twins) textile and clothing products. In this advanced digital ecosystem, the

process completely moves into the virtual space. Specialized AI algorithms integrated into the software perform an instant analysis of the mechanical and physical properties of the fabric precisely taking into account parameters such as resistance to stretching, coefficient of friction, weave density, weight, elasticity and drape. Based on these inputs, the real-time system faithfully simulates the behavior of the material and its interaction with adaptive three-dimensional digital avatars of the human body in motion. The combined application of AI analytics and 3D simulation models brings multiple, documented benefits for sustainable manufacturing processes:

1. Radical reduction of pre-production textile waste: Physical sampling of materials is reduced to an absolute minimum or completely eliminated from the cycle. Large fashion brands and manufacturing facilities can successfully approve and validate complete seasonal collections without a single meter of fabric being physically cut, saving resources and eliminating waste at the source.

2. Intelligent optimization of tailoring images (Computer-Aided Marker Making): The textile tailoring process has traditionally been a source of significant waste due to inefficient placement of patterns on the fabric. Today, advanced algorithms and machine learning systems driven by artificial intelligence calculate the most mathematically efficient possible arrangement of cut parts on a textile bale. By optimizing stacking in a fraction of a second, AI minimizes the empty space between cuts, reducing production waste on the line by significant percentages, which at the level of mass industrial production generates millions in material savings.

3. Predicting consumer behavior and preventing overproduction: By integrating AI models that analyze historical sales data and current trends from social networks, companies can test virtual garments on digital channels or through pre-order systems before making the decision to launch mass series production. This drastically reduces the risk of creating unsold goods (dead stock) which in the traditional model of fast fashion usually end up in illegal landfills in developing countries or are destroyed in industrial furnaces [7].

This digital revolution in design is directly linked to the broader concept of the digital fashion revolution, where virtual clothing and digital sampling are opening up new avenues to drastically reduce the carbon footprint of the entire sector, transforming the way consumers and manufacturers interact [7].

4. TRANSPARENCY AND DIGITAL PRODUCT PASSPORT (DPP)

While artificial intelligence successfully optimizes internal operational and design processes within the factories themselves, sustainability in a broader macroeconomic sense requires the establishment of absolute, uncompromising transparency and traceability along the entire and often fragmented global supply chain. The new Regulation on ecological design for sustainable products (Ecodesign for Sustainable Products Regulation - ESPR), adopted by the European Commission, mandates a strict legal obligation to introduce the Digital Product Passport (DPP) by the end of 2026 for all key industrial

sectors, with the textile and fashion sector being marked as an absolute priority for implementation.

4.1. Concept, parameters and technological architecture of DPP

DPP is defined as a decentralized, standardized digital file or structured database that faithfully tracks and documents a garment through absolutely all phases of its life cycle. Access to this verified data will be provided to end consumers, sustainability managers, logistics operators, customs authorities and recycling plants through integrated physical data carriers on the product itself, such as unique QR codes, high-frequency NFC (Near Field Communication) chips or robust RFID tags.In this complex information ecosystem, artificial intelligence systems play a critical role as they serve as a powerful analytical engine capable of collecting, structuring, and validating massive, heterogeneous data collected from geographically dispersed stages of the supply chain (from cotton fields, to chemical dyeing labs, to tailoring plants).

At the technical level, these systems rely on advanced search methods and semantic analysis, similar to architectures using Retrieval-Augmented Generation (RAG) systems and vector databases (like FAISS), to ensure maximum accuracy, prevent the structuring of false data and enable immediate verifiability of all entered product information [6]. According to official regulatory guidelines, DPP must accurately map and store parameters divided into key categories:

- Ecological footprint and emissions: Exact, quantified emission of carbon dioxide equivalents through all stages of production and transport, level of generated noise and waste gases.
- Resources and energy efficiency: Total amount and origin of consumed electrical and thermal energy; detailed volume of water consumption and level of effluent treatment (water footprint).
- Composition, toxicity and origin: Accurate data on raw material composition (percentage of virgin, organic or recycled fibres); presence and concentration of potentially dangerous chemicals and heavy metals.
- Circular potential and End-of-Life: Detailed, illustrated instructions for maintenance, possibilities and locations for repair, reuse, disassembly of components (zippers, buttons) and optimal chemical or mechanical recycling methods [10].

The DPP conceptual framework is seen as a fundamental pillar and technological enabler of the digital circular economy, as it provides the necessary transparency and infrastructure for monitoring material flows at the macro level [11]. From a technological point of view, the introduction of digital product passports represents a direct transition from theoretical models of sustainability to practical and operational application in modern industry [12].

4.2. Mechanisms of DPP contribution to sustainable business modelsA comprehensive implementation of the Digital Product Passport powered by AI analytics acts as a transformative catalyst for the fashion industry through three specific, practical mechanisms:

• Complete suppression of green washing and empowerment of consumers: By simply scanning the label with a smartphone before purchase, the consumer gets access to transparent and legally verified data on the origin and ecological price of the garment. This prevents brands from using manipulative and vague marketing terms (like the phrases "eco-friendly" or "sustainable") without solid, empirical evidence behind them.
• Catalysis of circular design (Design for Circularity): Access to precise DPP data allows designers to select only those materials and components that have a proven low environmental impact and can be easily recycled already at an early stage of sketching within the Clo3D system. AI systems can analyse millions of DPP cartons from previous production runs to suggest optimal fibre combinations that maximize garment longevity and durability.
• Automation and optimization of textile recycling: When a garment has reached the end of its life and arrives at the sorting centre, advanced robotic systems equipped with AI vision and DPP readers can instantly recognize the exact internal composition of the fabric (for example, recognizing a precise blend of 65% cotton and 35% polyester). This drastically speeds up, cheapens and automates the waste sorting process, which currently represents the biggest techno-economic barrier to mass and profitable textile recycling on a global level.

The introduction of digital passports and standardized data sheets on circularity, as foreseen by new international standards (ISO/DIS 59040), creates a unified language for all actors in the value chain, from producers to recyclers [8].

5. CHALLENGES AND PERSPECTIVES OF IMPLEMENTATION OF INTELLIGENT TECHNOLOGIES

Although the technological fusion of artificial intelligence, advanced 3D simulations and the concept of Digital Product Passport brings revolutionary environmental, economic and ethical benefits, the process of their comprehensive and mass implementation on a global level is accompanied by a series of extremely complex challenges and systemic barriers.

The first and most pronounced challenge is reflected in the high technological and financial barrier for small and medium-sized enterprises (SMEs), which form the backbone of the textile industry in many developing countries. While multinational fashion conglomerates possess the vast capital necessary to acquire expensive AI systems, purchase Clo3D licenses, train engineers and integrate complex DPP databases, smaller business entities face serious liquidity problems when trying to implement this transformation. Adapting legacy information and ERP systems within factories to meet rigid local and international environmental standards requires significant financial investment and a lengthy process of restructuring operational processes.

Another critical challenge relates to the problem of interoperability, data management and standardization at the global level. A typical supply chain in the fashion industry includes hundreds of independent actors (farms, mills, weavers, dyers, logistics centres) that are geographically dispersed around the world and often use completely different information systems and data formats. The exchange of critical information between them requires

strict adherence to unique open standards, such as ISO/DIS 59040, which defines product circularity data sheets. In addition, the complex issue of cyber security and protection of intellectual property and trade secrets opens up. Under the pressure of the regulator, companies are obliged to transparently share data on the chemical composition and origin of materials for the purpose of forming DPP, but at the same time they justifiably strive to protect their unique production formulas, technological innovations and commercially sensitive contracts from the competition. Due to all of the above, it is necessary to conduct further extensive, multidisciplinary scientific research that would define optimal political, legal and technological protocols for a safe and inclusive digital transition of the fashion industry [10].

6. CONCLUSION

Modern fashion and textile businesses can no longer maintain stability and profitability by maintaining outdated, linear, resource-intensive and non-transparent production models. The challenges posed to humanity by accelerated climate change, critical lack of primary natural resources and progressive ecological degradation of the planet require an urgent, radical and structural transformation of the entire fashion sector. Artificial intelligence, in direct synergy with sophisticated software tools for 3D simulation and virtual modeling such as Clo3D software, offers concrete, tested and highly efficient technological solutions for the elimination of material waste and optimization of resources already in the embryonic, creative phase of textile design.

Building on these optimized pre-production processes, the Digital Product Passport (DPP) concept successfully and efficiently closes the circle of the circular economy. DPP ensures full, unadulterated transparency of the supply chain, eliminates information asymmetry in the market, empowers consumer awareness and lays a solid economic foundation for the development of profitable repair, reuse and high-level automated textile recycling systems [10].

The upcoming mandatory introduction of these digital instruments by the end of 2026, encouraged by the rigorous and uncompromising regulatory framework of the European Union, no longer leaves business entities room for passivity and postponing radical changes. The implementation of intelligent technologies within the fashion industry has definitely ceased to be a matter of free choice, a tool for superficial ecological marketing or a means for isolated optimization of operational costs; it has become a fundamental legal and economic prerequisite for legal, competitive and sustainable business in the modern global market. Companies that timely, strategically and comprehensively integrate artificial intelligence into their operational and manufacturing processes will successfully minimize their environmental footprint, ensure full compliance with legislation and build a strong, long-term competitive advantage based on the trust and loyalty of modern, environmentally conscious consumers.

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CORPORATE SUSTAINABILITY AS A COMPETITIVENESS FACTOR IN THE CONTEMPORARY TEXTILE INDUSTRY

Review paper
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ABSTRACT: *In an environment characterized by intense global competition, increasingly demanding consumer expectations regarding responsible business practices, and stricter regulatory frameworks in environmental protection and social responsibility, sustainability has become one of the most significant factors influencing the long-term business success and competitiveness of companies in the textile industry. The subject of this research is corporate sustainability as a factor affecting the competitiveness of companies operating in the contemporary textile industry. The research problem focuses on determining the role of implementing corporate sustainability principles in enhancing competitiveness in the modern textile industry, as well as identifying the benefits of integrating sustainable practices into business strategies and operational processes. The aim of the paper is to analyze the importance of corporate sustainability as a competitive factor in the contemporary textile industry, with particular emphasis on how implementing sustainable business practices improves market position and ensures the long-term sustainable competitiveness of textile companies. The study is based on the assumption that corporate sustainability positively influences companies' ability in the textile industry to respond to market demands, optimize resource utilization, and develop stronger relationships with consumers and other stakeholders. Based on an analysis of relevant scientific and professional literature, it is concluded that corporate sustainability represents a strategic instrument for enhancing competitiveness and creating long-term value in the contemporary textile industry.*

Keywords: *Corporate sustainability, competitiveness, textile industry, sustainable business practices, competitive advantage.*

KORPORATIVNA ODRŽIVOST KAO FAKTOR KONKURENTNOSTI U SAVREMENOJ TEKSTILNOJ INDUSTRIJI

APSTRAKT: *U uslovima koje karakteriše intenzivna globalna konkurencija, sve izraženiji zahtevi potrošača za odgovornim poslovanjem i sve stroži regulatorni okviri u oblastima zaštite životne sredine i društvene odgovornosti, održivost postaje jedan od najznačajnijih faktora koji utiču na dugoročni poslovni uspeh i konkurentnost kompanija u tekstilnoj industriji. Predmet istraživanja koje je obavljeno u radu je korporativna održivost kao faktor koji utiče na konkurentnost kompanija u savremenoj tekstilnoj industriji. Problem istraživanja je utvrđivanje uloge koju primena principa korporativne održivosti ima u unapređenju konkurentnosti u savremenoj tekstilnoj industriji, kao i identifikovanje koristi koje proizlaze iz integrisanja održivih praksi u poslovne strategije i procese. Cilj rada je analiza značaja korporativne održivosti kao faktora konkurentnosti u savremenoj tekstilnoj industriji, uz stavljanje posebnog akcenta na načine na koje primena održivih poslovnih praksi omogućava unapređenje tržišne pozicije i obezbeđuje dugoročno održivu konkurentnost kompanija koje posluju u tekstilnoj industriji. U radu se polazi od pretpostavke da korporativna održivost ima pozitivan uticaj na sposobnost kompanija koje posluju u tekstilnoj industriji da odgovore na zahteve tržišta, optimizuju korišćenje resursa i izgrade kvalitetnije odnose sa potrošačima i ostalim zainteresovanim stranama. Na osnovu analize relevantne naučne i stručne literature, zaključuje se da korporativna održivost predstavlja strateški instrument za unapređenje konkurentnosti i stvaranje dugoročne vrednosti u savremenoj tekstilnoj industriji.*

Ključne reči: *Korporativna održivost, konkurentnost, tekstilna industrija, održivo poslovanje, konkurentska prednost.*

1. INTRODUCTION

The textile and apparel industry played a crucial role in the early stages of industrialization, driven primarily by simple technologies, labor-intensive production processes, and relatively low capital investment [1]. During the eighteenth and nineteenth centuries, the textile industry was the first sector to undergo industrialization in most countries. From the beginning of its development to the present day, the textile industry has been recognized as one of the sectors with significant negative environmental impacts, primarily reflected in pollution and the generation of large amounts of waste ultimately disposed of in landfills. The contemporary textile industry faces numerous challenges resulting from changes occurring across all segments of the business environment. Among the most significant changes affecting the textile industry are market globalization, rising consumer demand, evolving regulatory frameworks, and a growing emphasis on environmental protection and business sustainability. The textile industry is considered one of the sectors with a substantial impact on energy consumption, natural resource use, and waste generation. Due

to these adverse effects, companies in the textile industry are increasingly under pressure to align their business activities with the principles of sustainable development [2]. Under such circumstances, adherence to the principles of corporate sustainability, in addition to representing companies' ethical and social responsibilities, has become a significant factor influencing their long-term competitiveness.

2. CORPORATE SUSTAINABILITY

The term corporate sustainability refers to the integration of economic, environmental, and social dimensions into companies' business activities, strategies, and decision-making processes [3]. The primary objective of corporate sustainability is to enable companies to generate profits while simultaneously reducing the negative environmental impacts of their operations and contributing to the well-being of employees, local communities, and other stakeholders.

The implementation of the corporate sustainability concept in the textile industry is based on the responsible use of resources, the adoption of environmentally friendly materials and production methods, the improvement of working conditions, and the development of business models founded on the principles of the circular economy [4]. Corporate sustainability can be defined as the ability of companies to meet the needs of current stakeholders through their business activities without compromising the opportunities available to future generations to satisfy their own needs [3].

The concept of corporate sustainability is grounded in the responsible use of resources across all business functions, the reduction of negative environmental impacts, respect for ethical principles and employees' rights, and the creation of economic value in a sustainable manner. The growing importance of corporate sustainability in the contemporary textile industry is primarily a consequence of increasing demands for transparency and accountability in all aspects of business operations.

Corporate sustainability is based on aligning the economic, environmental, and social objectives of companies with the aim of creating long-term value and ensuring profitable business performance [3]. Operations within the textile industry generate significant negative impacts on the environment, particularly in the ecological dimension. Textile production is highly energy-intensive and requires substantial quantities of water and chemicals, while simultaneously generating large amounts of waste and greenhouse gas emissions. In addition to environmental concerns, the textile industry is also associated with significant issues related to working conditions and labor rights. The need to achieve the lowest possible production costs places strong pressure on companies to reduce labor expenses, which constitute a substantial share of total operating costs. As a result of these negative impacts, companies operating in the textile industry are increasingly expected to base all aspects of their business activities on the principles of sustainable development.

3. ADVERSE ENVIRONMENTAL IMPACTS OF THE TEXTILE INDUSTRY

The negative impacts of the contemporary textile industry on the environment are extensive and highly diverse. An additional concern is the fact that these adverse effects continue to

increase, making them an ever-growing threat. One of the most significant factors contributing to the expansion of the textile industry's environmental footprint is the development of fast fashion, which is based on low-cost, lower-quality products with short life cycles. Fast-fashion products are typically used for only one season before being discarded and becoming waste, despite often remaining fully functional and suitable for continued use. The development of the fast-fashion model has been driven by manufacturers' efforts to significantly increase sales volumes and profits while largely disregarding the substantial negative consequences for the natural environment and resource consumption [5].

The importance of corporate sustainability in the textile industry is best illustrated by data concerning the negative effects of clothing production. More than one billion garments are produced globally each year. The production of these garments generates over 1.2 billion tons of carbon dioxide emissions and releases more than 500,000 tons of microplastic fibers into aquatic ecosystems annually [6]. In 2024 alone, approximately 92 million tons of textile waste were generated throughout the various stages of the textile product life cycle [5]. More than half of this waste consisted of products discarded while still fully functional, often undamaged and suitable for continued use.

The negative impacts of the textile industry and the insufficient implementation of corporate sustainability principles can be clearly observed through the extremely low percentage of textile products that are recycled. Only 15-20% of total textile waste is collected for recycling or reuse, despite the fact that a substantial portion remains functional and reusable. More than 80% of discarded garments are sent to landfills or incinerated at the end of their life cycle, resulting in significant environmental pollution and unnecessary losses of the resources used in their production [7]. These numerous and substantial negative effects create a strong imperative for companies operating in the textile sector to implement corporate sustainability principles across all aspects of their business operations.

Over the past three decades, textile companies have increasingly focused on activities aimed at improving sustainability and reducing the negative impacts generated by their operations, particularly in the areas of environmental protection and resource utilization. By emphasizing corporate sustainability, companies seek to build an image of organizations that care about environmental protection and social responsibility. The importance of sustainability is further reinforced by the fact that consumers are increasingly considering the sustainability characteristics of fashion products when making purchasing decisions, making sustainability one of the most influential factors in consumer choice [7].

Textile companies can undertake numerous initiatives to reduce the adverse impacts associated with the production and use of their products. The most important of these include the production of environmentally friendly products, ensuring transparency throughout supply chains, minimizing environmental damage, and emphasizing product reuse, recycling, and the production of new goods from materials recovered from discarded textile products [8].

Corporate sustainability represents a contemporary business management concept that integrates environmental, economic, and social objectives into corporate strategies. Its primary purpose is to create long-term value for both the company and its stakeholders. The main difference between corporate sustainability and traditional approaches to management in the textile industry lies in the objectives pursued. Traditional approaches primarily focus on profit maximization, whereas corporate sustainability emphasizes achieving a balance between economic performance, environmental protection, and social responsibility.

The textile industry faces numerous sustainability-related challenges. Textile production requires large quantities of water, energy, and chemicals, making it one of the industries with the most significant impacts on the natural environment and local communities. According to the United Nations Environment Programme (UNEP), the textile industry contributes substantially to global carbon dioxide emissions and, due to the extensive use of dyes and chemicals during production processes, is among the largest contributors to water pollution worldwide [9,11]. The environmental consequences associated with textile production have led to increasing pressure from consumers, investors, and regulatory authorities on companies to improve the sustainability of their business models and operations.

4. CORPORATE SUSTAINABILITY AS A FACTOR OF COMPETITIVENESS IN THE TEXTILE INDUSTRY

The implementation of corporate sustainability enables companies to effectively and comprehensively meet the demands for transparency and responsible business practices imposed by consumers, investors, public authorities, and other stakeholder groups. The importance of corporate sustainability is reflected in the fact that it has become a significant source of competitive advantage in the contemporary textile industry [13,14]. The integration of sustainability principles into the operations of textile companies generates numerous positive outcomes, including reduced operating costs, more efficient resource utilization, enhanced corporate and brand reputation, and increased customer loyalty [9,10].

Adherence to sustainable business principles enables companies to manage risks related to climate change, market fluctuations, and regulatory requirements more effectively. The importance of sustainability in the modern textile industry extends far beyond its ethical dimension. Corporate sustainability has become a strategic instrument through which companies protect and strengthen their market positions and secure long-term competitiveness.

The textile industry is one of the sectors in which corporate sustainability plays a particularly important role. Companies operating in this industry face numerous challenges related to natural resource consumption, greenhouse gas emissions, waste management, and labor conditions throughout their supply chains. The adoption of sustainability-oriented business models, circular economy principles, and Environmental, Social, and Governance (ESG) standards enables textile companies to improve operational efficiency

and transparency while simultaneously strengthening consumer trust. Numerous studies indicate that the implementation of corporate sustainability and circular economy principles has a significant positive impact on the competitiveness of textile companies [12,15]. Increased competitiveness is primarily achieved through enhanced corporate reputation, greater investment activity, and the creation of long-term value resulting from sustainable business practices.

One of the distinctive characteristics of the textile industry is its high dependence on human labor, which increases the importance of the social dimension of sustainability. A large proportion of textile industry employees perform relatively simple tasks and receive low wages. Low production costs, in which labor costs represent a substantial component, are often a central element of cost-leadership strategies adopted by textile companies. Consequently, the implementation of corporate sustainability principles in this area may have certain short-term negative effects on competitiveness due to increased labor costs associated with improving working conditions and employee welfare [16]. However, these investments often generate long-term benefits through improved employee satisfaction, productivity, and corporate reputation.

The application of corporate sustainability principles can significantly enhance the competitiveness of textile companies. One of the most important benefits is increased operational efficiency resulting from the more rational use of resources. Investments in energy efficiency, renewable energy sources, material recycling, and waste reduction contribute to substantial reductions in operating costs and improvements in profitability [7]. Socially responsible business practices also create shared value for both companies and society. Consequently, investments in sustainability should not be viewed as additional expenses but rather as strategic investments that generate valuable competitive advantages.

In addition to economic benefits, corporate sustainability can significantly strengthen non-economic sources of competitiveness, particularly corporate reputation and brand value. Modern consumers increasingly consider sustainability-related factors when purchasing clothing, including product origin, production conditions, and environmental impacts associated with manufacturing processes. Research findings indicate that consumers tend to prefer products offered by brands that adhere to sustainability principles, conduct business responsibly, and maintain transparent supply chains [2]. In the textile industry, this trend is reflected in the growing popularity of sustainable fashion, increasing demand for products made from organic or recycled materials, and the wider adoption of circular economy models.

The implementation of corporate sustainability principles also facilitates access to financing sources, including investment funds and capital markets. Business sustainability has become an increasingly important factor in investment and financing decisions concerning textile companies. Organizations with higher levels of sustainability performance often enjoy easier access to capital, lower financing costs, and greater investor confidence [17]. Furthermore, compliance with international sustainability standards and transparent sustainability reporting have become important mechanisms for differentiation and the achievement of competitive advantages.

Research findings further suggest that textile companies that incorporate corporate sustainability principles into their operations demonstrate higher levels of risk management effectiveness compared to their competitors. Contemporary textile companies face numerous challenges, including resource scarcity, climate change, shifting consumer preferences, and evolving regulatory requirements [18]. Organizations that proactively integrate sustainability into their business strategies are generally more adaptable to change and more resilient to market disruptions. From a long-term perspective, one of the most significant competitive advantages generated through corporate sustainability lies in the development of stable and resilient business models capable of withstanding various environmental and market challenges.

5. CONCLUSION

Over the past two decades, there has been a continuous upward trend in consumer interest in clothing produced in accordance with corporate sustainability principles. This growing interest places an imperative on companies operating in the textile industry to invest further in innovation and the implementation of sustainable business practices. In addition to consumer pressure, companies are also facing obligations in the form of legal regulations, international standards, and investor requirements, which compel them to base their operations on the principles of social responsibility and transparency.

These changes have resulted in an increased importance of corporate sustainability, which has become a significant source of competitive advantage for companies. The most important positive effects of implementing corporate sustainability in textile companies include cost optimization, access to new markets, strengthened corporate reputation, and increased customer loyalty. The elements associated with corporate sustainability are complex and encompass all segments of corporate operations.

Corporate sustainability requires textile companies to use environmentally friendly raw materials, improve energy efficiency, reduce water consumption, recycle materials, and ensure responsible waste management. Its implementation also involves providing safe and fair working conditions, respecting human rights, and ensuring ethical business conduct across all stages of production. An increasingly important aspect of corporate sustainability is the circular economy, which aims to extend the life cycle of products through reuse, recycling, and repair.

In contemporary markets, corporate sustainability has become one of the fundamental and most important elements on which textile companies base their competitiveness. Through the integration of economic, environmental, and social aspects of business, textile companies can improve operational efficiency, reduce costs, strengthen brand reputation, attract investors more easily, and manage risks more effectively. In today’s business environment, characterized by increasing consumer demands and stricter regulatory frameworks, the implementation of sustainable business practices and adherence to corporate sustainability principles have become essential requirements. Without them, it is not possible to ensure profitability and long-term sustainable competitive advantages.

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CIRCULAR ECONOMY IN THE TEXTILE INDUSTRY AS A FACTOR OF FINANCIAL SUSTAINABILITY AND COMPETITIVENESS

Review paper
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ABSTRACT: *The modern textile industry faces significant environmental challenges due to high levels of waste, intensive resource consumption, and the short life cycle of products characteristic of the fast fashion model. In response to these limitations, the concept of the circular economy is gaining increasing importance, as it implies a transition from the linear model of production and consumption to a model based on reuse, recycling, and extending the life cycle of products.The aim of this paper is to analyze the role of the circular economy in improving the financial sustainability and competitiveness of textile companies. Special focus is placed on changes in the cost structure, opportunities for cost savings, development of new revenue sources, and the impact on business profitability.Research results indicate that the application of circular models may lead to increased costs in the short term, while long-term effects are reflected in improved efficiency, more rational use of resources, and a stronger market position of companies. It is concluded that the circular economy represents an important direction for the development of the textile industry and a key mechanism of its transition toward sustainable business.*

Keywords: *circular economy; textile industry; linear model; cost structure; sustainable business; textile recycling.*

CIRKULARNA EKONOMIJA U TEKSTILNOJ INDUSTRIJI KAO FAKTOR FINANSIJSKE ODRŽIVOSTI I KONKURENTNOSTI

APSTRAKT: *Savremena tekstilna industrija suočava se sa značajnim izazovima u oblasti zaštite životne sredine, usled visokog nivoa otpada, intenzivne potrošnje resursa i kratkog životnog ciklusa proizvoda karakterističnog za model brze mode. Kao odgovor na ova ograničenja, koncept cirkularne ekonomije dobija sve veći značaj, jer podrazumeva*

prelazak sa linearnog modela proizvodnje i potrošnje na model zasnovan na ponovnoj upotrebi, reciklaži i produženju životnog ciklusa proizvoda.Cilj rada je analiza uloge cirkularne ekonomije u unapređenju finansijske održivosti i konkurentnosti tekstilnih kompanija. Poseban fokus stavljen je na promene u strukturi troškova, mogućnosti za ostvarivanje ušteda, razvoj novih izvora prihoda i uticaj na profitabilnost poslovanja. Rezultati istraživanja ukazuju da primena cirkularnih modela može dovesti do povećanja troškova u kratkom roku, dok se dugoročni efekti ogledaju u unapređenju efikasnosti, racionalnijem korišćenju resursa i jačanju tržišne pozicije kompanija. Zaključuje se da cirkularna ekonomija predstavlja važan pravac razvoja tekstilne industrije i ključni mehanizam njene tranzicije ka održivom poslovanju.

Ključne reči: *cirkularna ekonomija; tekstilna industrija; linearni model; struktura troškova; održivo poslovanje; reciklaža tekstila.*

1. INTRODUCTION

The textile industry is one of the most significant sectors of the global economy, while simultaneously being one of the major sources of adverse environmental impacts. Intensive production, rapid consumption, and short product life cycles, which are characteristic of the fast-fashion model, have led to a substantial increase in textile waste and the inefficient use of resources.

Among consumption categories in the European Union, textiles rank fourth in terms of their negative impact on the environment and climate change, following food, housing, and transport [1]. The European Commission further indicates that the textile industry ranks third in the EU in terms of water and land use, and fifth in terms of greenhouse gas emissions and raw material consumption.

In addition to its environmental consequences, this business model also has significant economic implications. Short product life cycles and limited opportunities for reuse result in the loss of material value and the underutilisation of economic potential. It is estimated that more than USD 500 billion in textile product value is lost globally each year due to insufficient utilisation, premature disposal, and the absence of efficient reuse and recycling systems [2].

The textile industry is facing a growing waste-generation problem and low recycling rates, ranging between 15% and 20%, which further demonstrates the limitations of the linear business model [2]. An additional challenge arises from the hidden costs associated with waste management and negative environmental externalities, which are increasingly becoming subject to regulatory intervention, ESG requirements, and new sustainability standards.

These factors indicate that, although the linear fast-fashion model may be profitable and operationally efficient in the short term, it entails significant long-term financial risks. This further reinforces the need to transition towards more sustainable and circular business models.

In this context, the linear production model, based on the “take–make–dispose” principle, is increasingly being questioned from both sustainability and long-term economic efficiency perspectives. In response to these challenges, the concept of the circular economy has gained growing importance in contemporary research and business practice. Although the existing literature largely focuses on the environmental and social dimensions of sustainability in the textile industry, the financial implications of implementing circular business models remain insufficiently explored. It is particularly important to examine how the transition to a circular model affects companies’ cost and revenue structures, profitability, and long-term business sustainability.

2. THEORETICAL FRAMEWORK OF THE CIRCULAR ECONOMY IN THE TEXTILE INDUSTRY

The circular economy represents a systemic approach aimed at closing material and energy loops through reuse, recycling, and the extension of product life cycles. The primary objective of this concept is to preserve the value of resources within the economic system for as long as possible, while minimising waste and adverse environmental impacts [3]. Circular business models reduce dependence on primary raw materials and enable the creation of additional economic value through more efficient resource management [4].
The contemporary development of the circular economy has been further encouraged by regulatory and technological innovations, among which the concept of the Digital Product Passport is particularly significant. This instrument enables the monitoring of the entire life cycle of textile products, including the origin of raw materials, production methods, product use, and recycling options. In this way, it enhances transparency and facilitates the transition towards circular business models [5]. The introduction of such solutions also has significant financial implications, as it contributes to more efficient resource management, cost reduction, and stronger consumer and investor confidence.
The transition from a linear to a circular model brings about structural changes across all dimensions of business operations, ranging from resource use and waste management to cost structures and revenue streams. Table 1 presents the key differences between these two models from the perspective of relevant economic and environmental factors

Table 1. : Key Differences between the Linear and Circular Models in the Textile Industry

Factor	Linear Model	Circular Model
Resource use	Single use of raw materials: extraction, production, use, and disposal	Continuous circulation of materials through reuse, repair, and recycling
Waste management	High levels of waste; a large share of products ends up in landfills	Waste minimisation; materials are returned to the production cycle
Environmental impact	High resource consumption, pollution, and CO2 emissions	Lower carbon footprint, reduced resource consumption, and less waste
Economic approach	Focus on mass production and rapid product turnover	Value retention through product durability, repair, resale, and closed-loop systems
Product life cycle	Short product life cycle	Extended product life cycle
Revenue	One-time sales	Multiple revenue streams: sales, rental, resale, and repair
Cost structure	Lower initial costs; higher hidden costs of waste and inventory	Higher initial investment; lower total costs in the long term

Source: Authors' own interpretation

In the textile industry, the circular economy encompasses several interconnected forms of activity:

1. **Eco-design of products** – designing garments with a longer service life, improved repairability, and greater recyclability.
2. **Extension of product life cycles** – repairing, altering, maintaining, and reusing clothing.
3. **Reuse and resale models** – second-hand sales, resale platforms, and clothing exchange systems.
4. **Rental models** – renting clothing for special occasions or short-term use.
5. **Upcycling and remanufacturing** – transforming existing textile products into products of higher value.
6. **Textile recycling** – the mechanical and chemical processing of textile waste into new fibres or other products.
7. **Use of sustainable and recycled raw materials** – organic cotton, recycled polyester, regenerated fibres, and alternative materials.
8. **More efficient resource management** – reducing the consumption of water, energy, chemicals, and packaging in production, as well as increasing the use of renewable energy sources.
9. **Digital support for circularity** – Digital Product Passports, raw-material traceability, AI-based waste sorting, and transparent supply chains.

10. **Product take-back systems** – programmes that enable consumers to return used clothing to manufacturers for reuse or recycling.

From an economic perspective, these models alter the traditional cost and revenue structure of the textile industry. Although they often require higher initial investments in technology, logistics, and business organisation, they may lead to lower raw material costs, generate new revenue streams, enhance resilience to market risks, and strengthen long-term competitiveness [6]. At the macroeconomic level, their effects are reflected in the development of new markets, job creation, reduced import dependence, and lower environmental costs for society as a whole [7]. In addition to environmental considerations, the integration of financial and environmental indicators into business performance assessment is becoming increasingly important. Traditional accounting systems often fail to capture environmental costs, which may result in an inaccurate assessment of the actual profitability of both linear and circular business models. In this regard, contemporary approaches, such as material flow cost accounting, provide a more precise overview of total costs and facilitate the identification of potential savings [6]. Accordingly, the circular economy in the textile industry cannot be understood solely from an environmental protection perspective. It also requires an analysis of financial effects and long-term business sustainability, which constitutes the central focus of this paper.

3. TRANSITION COSTS AND INVESTMENTS REQUIRED FOR CIRCULAR BUSINESS MODELS

In contrast to the linear model, the circular economy entails a different cost structure, characterised by higher initial investment requirements but also by the potential for lower operating costs once the system has stabilised and economies of scale have been achieved. Consequently, the financial effects of circular business models tend to differ between the short-term transition phase and the medium- or long-term period of business operation. The implementation of circular business models requires investment in recycling technologies, reverse logistics, digital traceability, sustainable raw materials, and supply chain reorganisation. During the initial phase, these requirements may increase expenditure and capital needs [8].

Although technological innovation represents an important driver of circular economy development, certain studies also indicate the existence of the so-called rebound effect. According to the research conducted by Yerushalmi and Saha, some innovations in the textile sector may lead to an increase in overall consumption and production as a result of reduced costs and lower prices of final products, thereby diminishing or even offsetting some of the anticipated environmental benefits [9]. These findings suggest that technological innovation alone is insufficient and that the transition towards a circular economy also requires changes in consumer behaviour, an appropriate regulatory framework, and sustainable business models.

Greater use of secondary raw materials may contribute, over the long term, to more stable input costs and reduced dependence on primary commodity markets, particularly given the

volatility of energy and petrochemical prices, which significantly affect the cost of polyester as the dominant raw material in the textile industry.

One of the key challenges lies in the complexity of textile recycling, especially in the case of blended materials such as cotton, polyester, and elastane, which increases sorting and processing costs. Advanced recycling increasingly requires investment in automation, artificial intelligence, and material-composition identification systems. These technologies improve sorting efficiency, the quality of secondary raw materials, and process productivity, but require additional expenditure on sensors, robotics, software, and industrial automation [10]. The lack of developed recycling capacity has been identified as one of the main financial constraints on the fashion industry's transition towards a circular business model [11].

Numerous studies indicate that more efficient recycling systems and the closing of material loops can make a significant contribution to waste reduction and improved resource efficiency in the textile industry [12]. According to estimates by Boston Consulting Group and ReHubs, Europe will require between EUR 8 billion and EUR 11 billion in capital investment to achieve an annual textile-to-textile recycling capacity of 2.7 million tonnes by 2035, in addition to annual operating costs of between EUR 5 billion and EUR 6.5 billion [13]. Such investment provides a foundation for waste reduction, the development of domestic material streams, and the strengthening of industrial competitiveness in the coming period.

Additional costs arise from systems for collecting used garments, as well as from the transport, sorting, and storage of used products. However, efficiently organised reverse logistics systems can increase product utilisation, generate additional revenue through resale activities, and reduce the cost of purchasing new materials. According to the H&M Group Sustainability Disclosure for 2023, more than 29,000 tonnes of textiles were collected through its garment-collection programme, confirming the importance of developing effective product-return logistics.

A significant new cost category is associated with the introduction of the Digital Product Passport system, which requires investment in QR-code or RFID product identification, databases, ERP integration, and regulatory reporting. Greater transparency may strengthen consumer confidence, facilitate recycling, and improve future supply chain management. For small and medium-sized enterprises, these costs may represent a substantial barrier to adopting circular business models. Therefore, when implementing new requirements, the regulatory framework should take into account the proportionality of obligations, transitional periods, and the availability of technical and financial support.

An additional category of investment relates to product redesign in accordance with eco-design principles. This includes the development of more durable products, designs that are easier to repair, the use of recyclable materials, and a reduction in complex fibre blends. Such changes may increase the costs of product development, testing, and the adaptation of production processes, while simultaneously creating the basis for longer product life cycles and higher market value.

An important aspect of the transition also concerns investment in energy efficiency and renewable energy sources, including solar systems, heat pumps, heat-recovery systems,

and equipment modernisation. Such investment may reduce exposure to rising energy prices, contribute to more stable operating costs, and improve the sustainability of production.

Marketing and market-development activities also generate additional expenditure. Emerging models, such as resale, rental, and products made from recycled materials, require investment in promotion, consumer education, and confidence-building regarding product quality. Once the market has been developed, these models may generate new revenue streams and strengthen customer loyalty.

Transition costs also include employee training, the adaptation of internal procedures, and the development of new competencies in the fields of digitalisation, sustainability, and reverse-flow management.

Overall, the economic viability of circular business models should not be assessed solely on the basis of initial costs, but rather in terms of total product life-cycle costs, opportunities for the repeated monetisation of resources, and financial effects that become more pronounced following the implementation phase.

4. NEW REVENUE STREAMS AND THE ECONOMIC POTENTIAL OF CIRCULAR BUSINESS MODELS

In addition to affecting costs, the circular economy also contributes to the transformation of revenue structures in the textile industry. Unlike the traditional linear model, which is based on the one-time sale of products, circular business models enable product value to be retained and utilised for longer periods through second-hand sales, resale platforms, repair services, rental models, product take-back programmes, and material recycling. In this way, companies can monetise the same product multiple times throughout its life cycle—through its initial sale, resale, rental, repair, and the final recovery of material value.

The global transition towards circular business models in the textile industry is accelerating, driven by the development of resale markets, product reuse, sustainable materials, and new approaches to textile waste management. According to an analysis by Frost & Sullivan, the global market for circular economy and sustainable solutions in the textile industry generated revenues of USD 2.53 billion in 2023, with a projected compound annual growth rate of 13.8% for the period from 2024 to 2030 [14]. Within the hierarchy of circular business models, product reuse often generates greater economic value than recycling, as it preserves product functionality while requiring minimal additional processing costs. Consequently, resale, second-hand, and repair models represent particularly attractive revenue streams in the textile industry. Their expansion reflects changing consumer behaviour and the growing acceptance of more sustainable forms of consumption. Estimates indicate that the global second-hand apparel market could reach a value of USD 367 billion by 2029, while the United States market is expected to reach USD 74 billion. The online resale segment has recorded particularly dynamic growth, increasing by 23% in 2024, with its market value projected to reach USD 40 billion by 2029 [15]. A practical example of the profitability of the resale model is provided by the Vinted platform, which recorded a 36% increase in revenue in 2024, while its net profit

rose by 330% compared with the previous year [16]. These results confirm the commercial potential of the secondary apparel market. According to research published by ThredUp, 58% of surveyed consumers reported purchasing second-hand clothing during 2024 [15]. This finding indicates the growing acceptance of resale models and a gradual shift in consumer behaviour towards more sustainable consumption patterns.The development of second-hand markets varies across regions, as demand is influenced by household income levels, the affordability of new products, digital infrastructure, and the degree to which sustainable consumption patterns are accepted. The expansion of platforms such as Vinted, Depop, and The RealReal further confirms the increasing market value of the secondary fashion market and the continued growth of digital resale models.

According to selected market analyses conducted by Circular Carbon Markets, the implementation of resale, rental, and repair models, together with product take-back programmes, may contribute to revenue growth of between 12% and 18% among fashion and textile companies with well-established brands and direct customer relationships [17]. The actual financial effect depends on the specific business model and the extent to which circular practices have been implemented.

The expansion of the second-hand and resale markets is also evident in the Republic of Serbia. According to an analysis by IBISWorld, Serbia’s second-hand goods retail market, which includes used clothing, footwear, and other pre-owned products, is estimated to be worth EUR 32.3 million, with annual revenue growth of 17.4%. Between 2020 and 2025, the market recorded a compound annual growth rate of 19.9%, indicating its rapid expansion and the growing importance of product-reuse models in the retail sector. Furthermore, the development of digital platforms such as KupujemProdajem, Limundo, and Kupindo, together with the increasing number of vintage and second-hand shops in Belgrade and other cities, points to the gradual expansion of online resale models and changing consumer behaviour in the domestic market.

5. FINANCIAL EFFECTS OF IMPLEMENTING CIRCULAR BUSINESS MODELS IN THE TEXTILE INDUSTRY

Although circular business models often require higher initial investment, numerous studies indicate that they can generate significant financial benefits in the medium and long term through cost reductions, the development of new revenue streams, and greater business resilience. Empirical evidence suggests that the application of circular economy principles may reduce production costs by approximately 12% through the reuse and recycling of materials [18].

On the revenue side, fashion and textile companies with well-established brands and direct relationships with customers can generate additional income through resale, rental, and repair services, as well as product take-back programmes. Patagonia’s Worn Wear programme provides an illustrative example of this approach. By purchasing used Patagonia products, refurbishing them, and reselling them at prices equivalent to approximately 50%–60% of the price of new products, the company generates additional

margins while simultaneously strengthening customer loyalty and brand value. This approach further reinforces Patagonia's reputation as a sustainability-oriented company.

According to McKinsey & Company estimates, the development of the textile recycling industry in Europe could generate an annual profit potential of EUR 1.5–2.2 billion by 2030, while creating approximately 15,000 new jobs. This confirms that the circular economy may also represent a significant industrial opportunity [11]. The positive impact on the labour market is further supported by European Commission estimates indicating that between 20 and 35 jobs may be created for every 1,000 tonnes of textiles collected for reuse, particularly in the areas of sorting, logistics, repair, resale, and local service activities. These figures confirm the broader development potential of circular business models [1].

The considerable economic potential of the circular economy is also confirmed by a number of industry analyses, including estimates by Oliver Wyman [19] and reports published by the Ellen MacArthur Foundation [2]. According to these sources, circular business models in the fashion and textile sector could generate economic benefits ranging from USD 180 billion to USD 240 billion, primarily through more efficient resource use, the development of secondary markets, and the creation of new revenue streams.

Furthermore, the growth of the textile recycling market confirms that the circular economy is becoming an increasingly important field of investment and economic development. According to estimates by Grand View Research, the global textile recycling market was valued at approximately USD 4.97 billion in 2025 and is projected to reach USD 6.94 billion by 2033, representing a compound annual growth rate of 4.4% [20].

Academic evidence supporting the economic potential of circular business models is provided by Palea, Santhià, and Miazza, who indicate that circular economy strategies may positively affect corporate profitability, operational efficiency, and firm market value. Their research shows that capital markets tend to value companies that implement circular strategies more intensively, while investors and financial institutions increasingly incorporate sustainability and ESG performance into their risk assessments and financing decisions [21]. In this way, circular transformation may indirectly reduce the cost of capital and enhance the investment attractiveness of companies.

An additional financial benefit is reflected in reduced dependence on primary raw materials and lower exposure to their price volatility. This is particularly important in the case of polyester, the dominant synthetic fibre in the modern textile industry, whose production depends on petrochemical derivatives and fluctuations in oil and gas prices. Energy markets are characterised by pronounced price volatility caused by geopolitical risks, supply chain disruptions, and changes in global demand, all of which directly affect production costs. In the long term, the finite nature of non-renewable fossil resources represents an additional challenge. Greater use of recycled polyester and alternative materials may mitigate exposure to these market risks and contribute to greater cost stability for companies.

In this regard, the circular economy may contribute to cost stabilisation, revenue diversification, increased supply chain resilience, and improved long-term financial sustainability and competitiveness of companies.

6. CONCLUSION

The specific characteristics of the textile industry are reflected in its complex global supply chains, the high intensity of production and consumption, and the dominant application of the fast-fashion model, which is characterised by frequent collection changes and shortened product life cycles. These characteristics, together with the consumption patterns of contemporary society, further complicate the implementation of circular economy principles and contribute to increasing volumes of textile waste.

The results of the analysis indicate that the application of circular economy principles can significantly transform the financial structure of textile companies. Although the transition towards circular business models often requires substantial initial investment in recycling technologies, reverse logistics, digital traceability, and sustainable raw materials, in the long term it may contribute to lower material costs, more efficient resource use, and reduced exposure to price shocks in raw material markets.

At the same time, circular business models create new revenue streams through resale, rental, repair, upcycling, and recycling activities, thereby extending the economic life of products and generating additional value. The development of the secondary clothing market, digital resale platforms, and the expanding textile recycling industry confirms that the circular economy represents not only an environmental concept but also an increasingly important market opportunity.

It may be concluded that the circular economy in the textile industry does not constitute a universal or cost-free solution. Nevertheless, it represents a development pathway with considerable potential to improve corporate competitiveness, resilience, and long-term profitability. In the context of increasing regulatory requirements, changing consumer preferences, and growing pressure on resources, companies that initiate circular transformation at an earlier stage may achieve a significant strategic advantage.

At the macroeconomic level, the circular economy in the textile industry offers clear financial benefits through resource savings, the creation of new market opportunities, and greater systemic resilience. However, the transition at the level of individual companies remains challenging, particularly due to high investment costs, insufficiently developed infrastructure, and the misalignment of economic incentives across the value chain.

For the Republic of Serbia and other developing countries, the transition towards circular business models may represent an opportunity to modernise the textile industry, improve export competitiveness, and develop new market niches based on sustainable production and more efficient resource use.

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STANDARDIZATION AS A SUPPORT TO INNOVATION AND SUSTAINABLE DEVELOPMENT IN THE TEXTILE INDUSTRY

Professional paper
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ABSTRACT: *The textile industry faces increasing demands related to product quality, production efficiency, and the sustainability of textile products. In this context, standardization provides a structured framework for defining technical requirements, ensuring product comparability, and supporting the application of modern technologies in the manufacturing and testing of textile products. In Serbia, the Institute for Standardization of Serbia (ISS) is responsible for the adoption of Serbian standards and related documents, including the adoption of international and European standards at the national level. Through this process, national standards in the field of textiles become available for application in industry, contributing to the alignment of production, testing, and product evaluation with internationally recognized requirements. Textile standards define essential product characteristics, including fibre composition, mechanical properties, durability, colour fastness, maintenance, and labelling. Their application enables consistent quality control, facilitates the introduction of new materials and technologies, and supports the optimization of production processes. At the same time, they contribute to extending product lifetime and improving resource efficiency, which are key aspects of sustainable development and the transition to a circular economy.*
Recent developments in the textile sector, including circular economy models, smart textiles, and digital solutions such as the Digital Product Passport, further emphasize the importance of reliable and standardized product data. Such data provide a necessary foundation for improving product performance, supporting sustainable practices, and enabling the effective application of emerging concepts in the textile industry.

Keywords: *standardization, textiles, innovation, sustainability, circular economy, Digital Product Passport.*

STANDARDIZACIJA KAO PODRŠKA INOVACIJAMA I ODRŽIVOM RAZVOJU U TEKSTILNOJ INDUSTRIJI

APSTRAKT: *Tekstilna industrija suočava se sa sve većim zahtevima koji se odnose na kvalitet proizvoda, efikasnost proizvodnje i održivost tekstilnih proizvoda. U tom kontekstu,*

standardizacija obezbeđuje uređen okvir za definisanje tehničkih zahteva, uporedivost proizvoda i podršku primeni savremenih tehnologija u proizvodnji i ispitivanju tekstilnih proizvoda. U Srbiji je Institut za standardizaciju Srbije nacionalno telo za standardizaciju nadležno za donošenje srpskih standarda i srodnih dokumenata, uključujući preuzimanje međunarodnih i evropskih standarda na nacionalnom nivou. Na taj način srpski standardi iz oblasti tekstila postaju dostupni za primenu u industriji i doprinose usklađivanju proizvodnje, ispitivanja i ocenjivanja proizvoda sa međunarodno priznatim zahtevima.
Standardi u oblasti tekstila definišu važne karakteristike proizvoda, uključujući sastav vlakana, mehanička svojstva, trajnost, postojanost obojenja, održavanje i označavanje. Njihova primena omogućava doslednu kontrolu kvaliteta, olakšava uvođenje novih materijala i tehnologija i podržava optimizaciju proizvodnih procesa. Istovremeno, standardi doprinose produžavanju veka trajanja proizvoda i efikasnijem korišćenju resursa, što predstavlja značajan aspekt održivog razvoja i prelaska na cirkularnu ekonomiju. Savremeni pravci razvoja u tekstilnom sektoru, uključujući modele cirkularne ekonomije, pametni tekstil i digitalna rešenja kao što je digitalni pasoš proizvoda, dodatno ističu značaj pouzdanih i standardizovanih podataka o proizvodu. Takvi podaci predstavljaju neophodnu osnovu za unapređenje performansi proizvoda, podršku održivim praksama i efikasnu primenu novih koncepata u tekstilnoj industriji.

Ključne reči: *standardizacija, tekstil, inovacije, održivost, cirkularna ekonomija, digitalni pasoš proizvoda*

1. INTRODUCTION

The textile and apparel sector is undergoing a significant transformation driven by market expectations, technological development, environmental requirements and the need for transparent product information. Quality, durability, safety, resource efficiency and reliable labelling are no longer separate issues, but parts of a broader framework in which manufacturers, testing laboratories, public authorities and consumers require comparable and verifiable information.
The textile industry is also directly affected by changes related to sustainability, circular economy, digitalization and new means of product communication. In this context, standards provide a common technical language and enable the measurement, comparison and verification of product characteristics. They are important not only for traditional quality control, but also for the development of new materials, new production processes, environmental claims and digital product data.
The aim of this paper is to present standardization as a practical support mechanism for innovation and sustainable development in the textile industry, with a focus on the Serbian national standardization system. The paper outlines the role of the Institute for Standardization of Serbia, the functioning of technical committees, the fields covered by KS F038 and KS F072, and selected SRPS standards relevant to product quality, the circular economy, digitalization and the Digital Product Passport.

2. STANDARDIZATION AS A SUPPORT TO INNOVATION AND SUSTAINABILITY IN TEXTILES

2.1. Standardization framework in Serbia

The Institute for Standardization of Serbia is the national standardization body responsible for activities related to the development, adoption, publication, maintenance, review and withdrawal of Serbian standards and related documents. Through the adoption of international and European standards as Serbian standards, the Institute connects national economic and regulatory needs with international and European standardization processes. The strategic priorities of the Institute include the adoption of Serbian standards, greater availability of standards in Serbian, cooperation with interested parties, digitalization of processes and participation in international and European standardization organizations.

The development, publication, maintenance, review and withdrawal of Serbian standards and related documents are regulated by the Internal Rules of Standardization. The establishment and work of technical committees are regulated by a separate part of these rules. These documents are harmonized with the Law on Standardization, the founding acts of the Institute and the rules of international and European standardization organizations [5], [6].

Technical committees are the expert bodies through which the professional work of the Institute is carried out in specific fields. Their work is based on the voluntary participation of interested parties, including industry, public authorities, universities, laboratories, consumers and other organizations. In the textile sector, this is particularly important because practical needs from production, testing, import, inspection and market communication can be transferred into the national standardization process.

Standardization is not limited to the formal adoption of documents. It also represents a mechanism for connecting experts, institutions and industry with European and international technical requirements. In this way, standards become an important tool for improving product quality, increasing market transparency and supporting sustainable industrial development.

2.2. Technical committees in the textile field: KS F038 and KS F072

The work of technical committees is especially important in areas where production, testing, safety and market communication are closely connected. In the textile field, two committees are particularly relevant: KS F038, Textiles, and KS F072, Textile machinery and accessories.

The scope of KS F038, Textiles, covers standards in the field of fibres, yarns, threads, cords, ropes, apparel and other manufactured textile materials. It also includes testing methods, terminology and definitions, raw materials, auxiliary materials and chemical products used for production and testing, as well as specifications for textile products. The committee also covers certain wall coverings. KS F038 follows the work of ISO/TC 38, CEN/TC 248 and CEN/TC 99 [7].

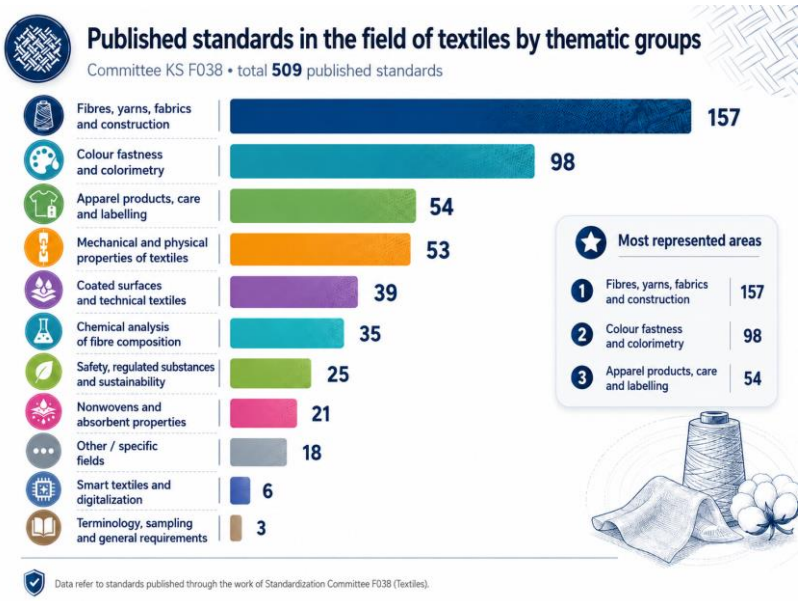

Figure 1: Published standards in the field of textiles by thematic groups, Committee KS F038. *Source: Prepared by the authors on the basis of ISS records on published standards, 26 May 2026.*

Based on an internal classification prepared for this paper from ISS records, KS F038 includes 509 published standards. The grouping is an analytical overview rather than an official committee classification. The largest groups relate to fibres, yarns, fabrics and construction; colour fastness and colorimetry; apparel products, care and labelling; and mechanical and physical properties of textiles. These areas confirm that the core of textile standardization is linked to product composition, durability, performance and user information, while newer groups such as sustainability, smart textiles and digitalization indicate future development directions.

KS F072, Textile machinery and accessories, prepares standards in the field of textile machinery and accessories, including machinery for dry-cleaning and industrial laundry. The committee follows the work of ISO/TC 72 and CEN/TC 214, as reflected in its business plan [8]. The thematic overview of 84 published standards shows that the most represented areas are weaving, knitting and fabric manufacturing equipment, safety requirements for textile machinery, and noise testing and noise reduction.

This structure reflects the practical needs of users and manufacturers of textile machinery: safe operation, reliability, compatibility of equipment and measurable noise-related performance. The role of these standards is therefore connected not only with safety, but also with modernization, process control and resource-efficient production.

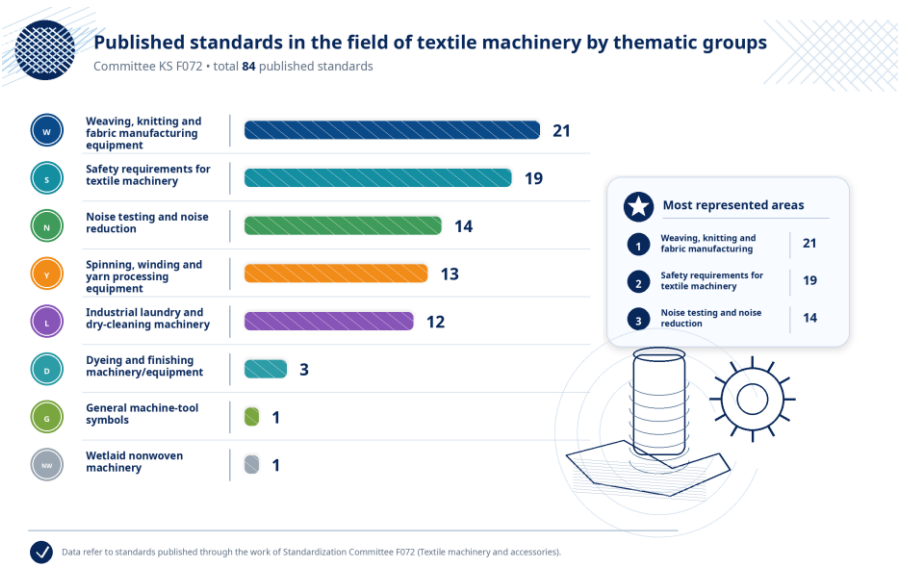

Figure 2: Published standards in the field of textile machinery by thematic groups, Committee KS F072. *Source: Prepared by the authors on the basis of ISS records on published standards, 26 May 2026.*

2.3. Selected SRPS standards supporting product quality and comparability

Innovation in textiles can be accepted by the market only when product characteristics are measurable, repeatable and comparable. Standards provide the technical basis for this process because they define terminology, testing conditions, test methods, classification systems and requirements for product information.

Within KS F038, this role is supported by standards such as SRPS EN ISO 139:2007, which defines standard atmospheres for conditioning and testing, the SRPS EN ISO 1833 series for quantitative chemical analysis of fibre mixtures and the SRPS EN ISO 105 series for colour fastness testing. These standards are important because they enable comparable test results and reduce uncertainty in communication between producers, laboratories, buyers and other interested parties.

Durability and use-phase performance are supported by standards such as SRPS EN ISO 105-C06:2016 for colour fastness to domestic and commercial laundering, SRPS EN ISO 5077:2010 for dimensional change in washing and drying, the SRPS EN ISO 12945 series for pilling, fuzzing and matting, and the SRPS EN ISO 12947 series for abrasion resistance by the Martindale method. These standards are directly connected with product lifetime, consumer satisfaction and the possibility of verifying product claims.

Product information is also an important part of textile quality. SRPS EN ISO 3758:2024, which relates to care labelling symbols, provides a basis for clear and standardized communication about maintenance. In practice, proper care information can contribute to longer product use, fewer consumer complaints and more responsible consumption.

In this way, classical textile standards remain relevant even in the context of new sustainability requirements. Reliable information on fibre composition, dimensional stability, colour fastness, abrasion resistance and care instructions is necessary both for traditional quality control and for future digital systems that will rely on verified product data.

2.4. Standards supporting sustainability, circular economy and digitalization

Sustainability requirements increasingly depend on reliable and verifiable information. In the textile industry, environmental communication must be based on clear terminology, recognized methods and transparent data. SRPS CEN/TS 16822:2016 is relevant because it deals with self-declared environmental claims and the use of terms in relation to textiles and textile products. This is important for reducing ambiguity in environmental communication and limiting the risk of misleading claims.

A specific environmental issue is the release of microplastics from textile sources. SRPS EN ISO 4484-1:2023 specifies a method for determining material loss from fabrics during washing, while SRPS EN ISO 4484-3:2023 deals with the measurement of collected material mass released from textile end products by the domestic washing method. At the time of drafting this paper, the national adoption project nkSRPS EN ISO 4484-4:2025 was also under development, indicating the further extension of the series towards quantitative thermal or gravimetric analysis of certain synthetic materials released from fabrics during washing.

The terminology basis is provided by SRPS EN ISO 5157:2023, Textiles — Environmental aspects — Vocabulary. Circularity-related standardization is also developing through projects such as dnaSRPS CEN/TS 18272-1:2025, intended to provide general principles and guidance for the circular economy of textile products, and prSRPS CEN/TS 18272-2:2026, which addresses design for circularity.

The Digital Product Passport should not be understood merely as an IT solution. Its value depends on the reliability of the data entered into the system. For textiles, information on fibre composition, care, durability, chemical content, repairability, recyclability, recycled content and microplastic release must be based on recognized terminology and test methods. Document CWA 18186:2025 gives guidance for setting up Digital Product Passports, while CWA 18291:2025 deals specifically with data collection, traceability and transparency in textile supply chains in the context of the Digital Product Passport.

Smart textiles are another emerging field. SRPS CEN ISO/TR 23383:2021 provides definitions, categorisation, applications and standardization needs for smart or intelligent textiles. More specific examples are SRPS EN ISO 24584:2022, which defines a test method for sheet resistance of conductive textiles using a non-contact method, and SRPS EN ISO 17971:2025, which defines a test method for determining screen-touch properties of fabrics.

Within the scope of KS F072, machinery standards also support sustainable production. The SRPS EN ISO 11111 series deals with safety requirements for textile machinery, the SRPS EN ISO 9902 series provides rules for testing noise emitted by textile machinery, SRPS EN ISO 23771:2016 gives guidance for designing textile machinery with reduced

noise emissions, and the SRPS EN ISO 8230 series covers safety requirements for dry-cleaning machines. These documents are relevant because sustainable production also depends on safe, efficient and well-controlled machinery.

Table 1: Examples of standards and standardization documents supporting innovation and sustainability in textiles

Area	Examples of standards/documents	Relevance
Product quality, durability and care	SRPS EN ISO 139:2007; SRPS EN ISO 105 and 1833 series; SRPS EN ISO 5077:2010; SRPS EN ISO 12945/12947 series; SRPS EN ISO 3758:2024	Comparable testing, reliable product information, quality control and longer product lifetime.
Environmental claims and circularity	SRPS CEN/TS 16822:2016; SRPS EN ISO 4484-1:2023 and SRPS EN ISO 4484-3:2023; nkSRPS EN ISO 4484-4:2025 (project); SRPS EN ISO 5157:2023; dnaSRPS CEN/TS 18272-1:2025 and prSRPS CEN/TS 18272-2:2026 (projects)	Verified claims, microplastic assessment, environmental terminology and circular design principles.
Digital data and smart textiles	CWA 18186:2025; CWA 18291:2025; SRPS CEN ISO/TR 23383:2021; SRPS EN ISO 24584:2022; SRPS EN ISO 17971:2025	Traceability, data credibility, interoperability and new functional properties.
Textile machinery	SRPS EN ISO 11111 series; SRPS EN ISO 9902 series; SRPS EN ISO 23771:2016; SRPS EN ISO 8230 series	Machinery safety, noise reduction, reliable operation and sustainable production.

Source: Authors' synthesis based on ISS records for KS F038 and KS F072. Selected projects are included where they indicate further development of circularity-related requirements.

2.5. Discussion of standardization priorities in the textile sector

The thematic overview of published standards shows that textile standardization in Serbia is strongly grounded in traditional areas of product quality, testing, care and labelling. This is an advantage because these areas provide the measurable foundation required both for conventional quality assurance and for new sustainability-related requirements. Standards on colour fastness, mechanical properties, fibre composition and care labelling are also relevant for digital product data because they provide evidence behind product claims.

At the same time, the smaller number of standards in areas such as smart textiles, digitalization and sustainability indicates the need for increased attention. For KS F038,

further work should combine established testing standards with more active monitoring of documents related to environmental claims, microplastics, circularity, traceability and digital product information. For KS F072, priorities remain machinery safety and noise reduction, with additional attention to machinery-related aspects of efficient and sustainable production.

In practical terms, standards support communication between industry, testing laboratories, public authorities and consumers. They are not only technical documents used in laboratories or production facilities, but also provide a framework for describing product characteristics, confirming quality, supporting environmental claims and preparing reliable data for future digital systems.

The importance of standards is expected to further increase with the development of circular economy models and the Digital Product Passport. These concepts require data that are not only available, but also comparable, structured and credible. The connection between textile standards, machinery standards, environmental requirements and digital data systems therefore represents one of the key future priorities for the textile sector.

3. CONCLUSION

Standardization in the textile industry is a practical tool that supports quality, safety, comparability, innovation and sustainable development. Through the work of the Institute for Standardization of Serbia and its technical committees, international and European standards are made available to interested parties in Serbia, while national experts are enabled to participate in European and international standardization processes.

The analysis of KS F038 and KS F072 shows that published standards cover both established and emerging areas. The selected Serbian standards and standardization documents discussed in this paper are relevant to fibre composition, colour fastness, care labelling, abrasion and pilling resistance, environmental claims, microplastics, the circular economy, smart textiles, machinery safety and noise reduction.

In the context of the circular economy and the Digital Product Passport, standards will become even more important because product data must be reliable, interoperable and accessible. Further development of standardization in the textile field should therefore continue to connect established testing and quality requirements with new topics such as circularity, traceability, digital product information and sustainability in textile production and use.

The role of standardization should be understood not only as a formal technical activity, but also as practical support for innovation, industrial development and responsible market communication. For the textile industry, this means that standards can contribute to better product quality, reduced environmental impact, more reliable environmental information, safer production processes and stronger alignment with European and international sustainability goals.

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CORRECTION OF NORMS USING THE SE-ERGO METHODOLOGY IN THE GARMENT INDUSTRY

Professional paper
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ABSTRACT: *This paper analyses the SE-ERGO methodology as an integrated framework for the identification, assessment and control of ergonomics risks and norms in the garment industry. The SE-ERGO methodology combines systems engineering with the principles of applied ergonomicss, enabling organisations to take a structured approach to improving working conditions and reducing musculoskeletal disorders, which are extremely prevalent in garment production. A five-phase model of SE-ERGO methodology application is presented, along with examples of interventions at typical workstations in garment manufacturing. The results of the analysis indicate a 40–55% reduction in musculoskeletal disorders, a productivity increase of up to 17%, and a significant improvement in worker satisfaction.*

Keywords: *SE-ERGO methodology, ergonomics, garment industry, musculoskeletal disorders.*

KOREKCIJA NORMI PRIMENOM SE-ERGO METODOLOGIJE U INDUSTRIJI ODEĆE

APSTRAKT: *Rad analizira SE-ERGO metodologiju kao integrisani okvir za identifikaciju, procenu i kontrolu ergonomskih rizika i normi u sektoru industrije odeće. SE-ERGO metodologija objedinjuje sistemsko inženjerstvo sa principima primenene ergonomije, omogućavajući organizacijama da strukturirano pristupe unapređenju uslova rada i smanjenju mišićno-skeletnih poremećaja koji su izuzetno učestali u proizvodnji odeće.*
Prikazan je petofazni model primene SE-ERGO metodologije, uz primere intervencija na tipičnim radnim mestima u konfekcijskoj proizvodnji. Rezultati sprovedene analize ukazuju na smanjenje mišićno-skeletnih poremećaja za 40–55%, porast produktivnosti do 17% i značajno povećanje zadovoljstva radnika.

Ključne reči: *SE-ERGO metodologija, ergonomija, industrija odeće, mišićno-skeletni poremećaji.*

1. INTRODUCTION

The global garment and textile industry employs well over 75 million workers, the vast majority of whom are exposed to a high risk of developing musculoskeletal disorders (MSDs). Repetitive movements, static working postures, high work pace, inadequate equipment and poorly ergonomicsally designed workstations are the primary causes of occupational disease in this sector [1,6].
Traditional approaches to ergonomicss in the garment industry are often reactive - intervention occurs only after workers' health problems have already emerged.
According to data from the International Labour Organization, musculoskeletal diseases account for more than 59% of all occupational diseases in the manufacturing sector. In the garment industry, epidemiological studies consistently report [1,6,7]:

- Neck and shoulder pain in 60–75% of sewing machine operators.
- Carpal tunnel syndrome prevalence 3–4 times higher than in the general population.
- Low back pain affecting 45–65% of workers in cutting and packaging processes.
- An average of 18–24 lost working days per worker per year due to musculoskeletal disorders.

Beyond the humanitarian dimension, these figures have direct economic implications: treatment costs, worker replacement and reduced productivity account for 3–6% of total labour costs in a typical garment enterprise [1,2]. The SE-ERGO methodology therefore offers an alternative: a proactive, systemically structured approach that integrates ergonomics considerations into every phase of the design and management of work processes.

2. THE SE-ERGO METHODOLOGY

The SE-ERGO methodology was developed in response to the limitations of classical ergonomics approaches that focus exclusively on the individual workstation, without taking into account the broader systemic context in which that workstation is embedded. The methodology builds on two key theoretical directions [2]:

- Systems Engineering theory - which views the work system as a whole in which elements are mutually interdependent.
- Applied ergonomicss.

The SE-ERGO methodology may be defined: as a structured, iterative framework for the systematic identification, analysis, prioritisation and control of ergonomics risks, integrated with the processes of work design, planning and organisational management.
Four key principles of the SE-ERGO methodology:

- Holism – the workstation is not viewed in isolation but as part of a broader work, organisational and physical environment.

- Participativeness – workers actively participate in problem identification and solution development (participatory ergonomicss) [7].
- Measurability – every intervention must be accompanied by quantitative indicators measured before and after implementation.
- Iterativeness – the process is continuous, with ongoing monitoring and adjustment of interventions.

The five-phase model constitutes the core of the SE-ERGO methodology and defines the sequence and content of activities from the initial analysis through to long-term monitoring.

Table 1: Five-phase model

Phase	Name	Objective	Output
1	Systemic workstation analysis	Identification of ergonomicsc risks in the production process	Risk map by workstation
2	Exposure assessment	Quantification of physical workload	RULA/REBA scores, load indices
3	Definition of interventions	Planning process and equipment corrections	Improvement action plan
4	Implementation	Introduction of ergonomics solutions into practice	Modified workstation/process
5	Evaluation and monitoring	Measurement of intervention effects	Improvement report, KPIs

The SE-ERGO methodology is not tied to a single specific assessment tool; rather, it integrates a range of standardised methods selected according to the characteristics of the work task.

Table 2: Ergonomics tools

Method	Application	Output	**Limitations**
RULA	Upper extremities, neck, trunk [4]	Score 1–7 (action level)	Does not cover dynamic tasks
REBA	Whole body, unstable postures [3]	Score 1–15 (risk level)	Requires real time observation
NIOSH	Manual lifting [5]	Recommended Weight Limit (RWL)	Lifting only, not pushing/pulling
Strain Index	Distal extremities – fine motor tasks	SI value (> 5 = risk)	Specific to manual activities

The selection of the appropriate tool is based on: the body part under primary load, the dominant type of load (repetitiveness, force, posture, vibrations), the availability of resources for method application, and the specific requirements of the applicable regulatory framework.

3. APPLICATION OF THE SE-ERGO METHODOLOGY IN THE GARMENT INDUSTRY

The garment industry is characterised by a high share of manual labour, short operation cycles (often below 30 seconds), intensive use of the upper extremities, and predominantly seated or standing working positions. Analysis of typical workstations in the garment industry identifies the following categories of ergonomics risks:

- High-intensity repetitive movements (sewing, cutting, packaging).
- Static muscle loading (neck and shoulders during sewing, back during quality control).
- Adverse working postures (neck flexion, wrist extension, trunk rotation).
- Contact stress (pressure of the table edge on forearms, tools on hands).
- Combined loading (simultaneous high repetitiveness, force and unfavourable body posture).

The analysis encompassed: a review of medical documentation (3 years), semi-structured interviews with 40 workers (random sample of 17%), video recording of 12 representative work operations, and analysis of work organisation (norms, breaks, rotations). Six high-risk workstations were identified (RULA score > 5) and 4 workstations with moderate risk (RULA score 4–5). A high correlation was found between the RULA score and reported musculoskeletal complaints ($r = 0.78$, $p < 0.001$).

A detailed assessment of high-risk workstations was carried out using RULA (upper extremities, neck, trunk) and NIOSH:

- Mean RULA score at sewing machines: 6.4 (action level 4 – immediate intervention required).
- Mean REBA score during cutting: 8.1 (high risk, intervention required).
- RWL for manual loading of fabric bales: 12.3 kg (vs. actual bale weight of 28 kg – lifting index 2.28).

An interdisciplinary ergonomics team prepared an action plan with 23 interventions, categorised by type:

- Engineering controls (10): lift tables, adjustable chairs, handling aids.
- Administrative controls (8): task rotation, new micro-breaks, revision of norms.
- Worker education and training (5): manual handling technique, individual workstation adjustment.

Table 3: Key Performance Indicators

Indicator (KPI)	Before SE-ERGO	After SE-ERGO
Mean RULA score (sewing operators)	6.4	3.0
MSD incidence rate (per 100 workers)	19	9.5
Sick days lost annually	1,240	680
Productivity (units/hour per worker)	42	49
Worker satisfaction (NPS scale, 0–10)	5.2	8.0

3.1. Norm Correction as an Ergonomics Intervention

Correction of work norms represents one of the key administrative ergonomics interventions within the SE-ERGO methodology. A norm in the garment industry defines the minimum number of operations (sewing, cutting, packaging) that a worker must complete during a work shift or working hour. When a norm is set without taking ergonomics load into account, it becomes a direct cause of excessive exposure to MSD risks. [1,2]

The SE-ERGO methodology introduces the concept of the corrected output: the norm is adjusted on the basis of the measured ergonomics load of the workstation, whereby an appropriate correction factor (Kf) is applied for each risk level. This approach ensures that the productivity requirement remains within the physiological and biomechanical capacity of the worker while simultaneously preserving the overall efficiency of the process. [2]

The correction factor Kf is not a linear function of the RULA score; rather, it is determined on the basis of action levels defined by the RULA method, in combination with physiological norms from standard EN 1005-4. The upper and lower thresholds were set empirically based on the results of studies on muscle fatigue and recovery in repetitive operations in the textile industry. [4,6,9]

The basic formula for norm correction within the SE-ERGO methodology is:

$$Nk = N0 \times Kf \qquad (1)$$

where:

Nk- corrected norm (units/shift or operations/hour)

N0 - initial norm prior to ergonomics assessment

Kf - correction factor, determined on the basis of the ergonomics score

Table 4: Example of norm correction

Workstation	Kf	Norm before (units/shift)	Norm after (units/shift)
Sewing operator	0.85	320	272
Manual cutting	0.75	180	135
Ironing	0.87	240	209
Packaging	0.90	400	360
Quality controller	0.93	500	465

The correction factor is not a permanent solution, but a temporary measure until engineering controls (ergonomics equipment, process reorganisation) are implemented that will enable a return to the original or even higher norm with less physiological effort. This is consistent with the NIOSH control hierarchy and ISO 45001 standards. [5,10]

Norm correction in Serbia also has a legal dimension. The Law on Occupational Safety and Health obliges employers to organise work in a manner that does not endanger the safety and health of workers, which implicitly includes adjusting norms to the physiological capacities of workers [11].

4. CONCLUSION

The SE-ERGO methodology represents an effective, measurable and economically justified approach to managing ergonomics risks in the garment industry. The five-phase model, from systemic analysis through to evaluation and monitoring, provides a structured framework that can be adapted to enterprises of varying sizes and resources.

The case study and tabular presentations in this paper demonstrate that consistent application of SE-ERGO principles can result in a 40–55% reduction in musculoskeletal disorders, a 45% reduction in sick days, a productivity increase of up to 17%, and an ROI exceeding 100% in the first year.

For the garment industry in Serbia and the region, the systemic application of ergonomics methodologies such as SE-ERGO is not a luxury but a strategic necessity. With growing demands from global brands and EU regulations regarding social responsibility in supply chains, factories that invest in safe and healthy working conditions gain a competitive advantage that outweighs the costs of implementation.

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NEW PUBLIC RELATIONS PRACTICES IN THE FASHION AND TEXTILE INDUSTRY

Review paper
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ABSTRACT: *The most important contemporary world-wide trends – development of new communication technologies and, consequently, new communicative practices, and, appearance of a number of crisis situations – which began in 2008, affect all aspects of society, including economic life. Social media, for instance, are increasingly integrated into contemporary world, which means, vast majority of people are exposed to what they see online, especially, when it comes to fashion. It becomes difficult not only for customers to follow trends, but also for companies to advertise and, more importantly, sell their products. Numerous industrial sectors, including the textile and fashion companies, are exposed to various threats. Textile and fashion companies, due to a fast changing business environment, try to find out more appropriate mechanisms in order to respond to the number of new challenges and tasks. Solving any problem, on the other hand, mainly depends on the achieved level of public relations development as a recognizable business function. The crucial goal of this study explains and highlights the role of public relations in contemporary business environment, particularly from the standpoint of companies that dominate in the textile and fashion industry. The first part of the paper depicts the role of public relations in general. The central part of this paper focuses on public relations practices that deal with the development of new communicative practices, on one hand, and, crisis situations, on the other hand. We also pay attention to potential communication strategies, developed within public relations field that can help the textile industry to resolve any problem under conditions of risk.*

Keywords: *public relations, new communicative practices, social media, textile and fashion industry, customer relations.*

NOVE PRAKSE ODNOSA S JAVNOŠĆU U MODNOJ I TEKSTILNOJ INDUSTRIJI

APSTRAKT: *Najznačajniji savremeni trendovi u svetu – razvoj novih komunikacionih tehnologija i, u skladu s tim, novih komunikacionih praksi, te izbijanje brojnih kriznih situacija – uveliko se odražavaju na sve aspekte modernih društava, uključujući i oblast ekonomije. Društveni mediji, na primer, sve više su integrisani u suvremeno poslovanje tako da se ogromna većina ljudi izlaže onom što vide onlajn, naročito kada se radi o modi. Kupcima postaje sve teže da prate trendove kao i preduzećima da se oglase i prodaju svoje proizvode. Mnoge privredne grane, uključujući odevnu i modnu industriju, izložene su svakovrsnim pretnjama i izazovima. Tekstilne i modne kompanije, zbog poslovne sredine koja se brzo menja, pokušavaju da pronađu delotvornije načine kako bi odgovorile na nove izazove i zadatke. Traganje za rešenjem nekog problema, s jedne strane, uglavnom ovisi od dostignutog nivoa razvoja odnosa s javnošću kao distinktivne poslovne funkcije. Glavni cilj ovog rada je da objasni i istakne ulogu odnosa s javnošću u savremenoj poslovnoj sredini polazeći, u prvom redu, od praksi koje dominiraju u tekstilnoj i modnoj industriji. U prvom delu rada ukazuje se na opštu ulogu odnosa s javnošću. Središnji deo rada se usredsređuje na aktivnosti odnosa s javnošću koje su usmerene na razvijanje novih komunikacionih praksi, s jedne, i, krizne situacije, s druge strane. Autori takođe posvećuju pažnju potencijalnim komunkacionim strategijama, kreiranim unutar odnosa s javnošću, koje mogu pomoći kompanijama tekstilne industrije da lakše reše bilo kakvi problem u uslovima rizika.*

Ključne reči: *odnosi s javnošću, nove komunikacijske prakse, društvene mreže, tekstilna i modna industrija, odnosi s kupcima.*

1. INTRODUCTION

The term "public relations" (PR) refers to the management of relations between one organization and the public, that is, the target public. PR are also a mechanism for positioning the organization in the public. The core of the public relations is comprised of the concepts of communication, organization and public [1]. The essence of the public relations is mainly embodied in the key categories such as "reputation, perception, credibility, trust, harmony and mutual understanding" [2, p. 7-8]. The key word in PR is "reputation" [3, p. i]. Reputation is being achieved on the basis of "understanding, trust, support, readiness for cooperation and agreement" [4, p. 94]. Filipović and Kostić-Stanković use 11 key categories to describe public relations: "reputation, image, identity, perception, credibility, trust, charm, mutual understanding, truthfulness and through information" [5, p. 7]. Wilcox and Cameron believe that the essence of public relations is embodied in the following categories: deliberateness/intention, planning, performance, public interest, (feedback / two-way) communication and management function [6]. Vladimirović believes that PR are “authentic and modern type of interpersonal communication, promotion and growth of the organization, together with its goods and

services" [7, p. 245]. PR are, in a way, "a milder form of winning the favour" of both general and specific segments of the public [8, p. 204]..

Public relations have largely entered a qualitative, new development phase - the digital age. This period is mainly characterized by the introduction of new communication technologies into the practice of PR [9-13]. The development of information technologies has led to an increase in the number of the employees in the information sector. Computers are becoming more accessible to more and more people. Digital public relations, based on the application of modern Internet technologies, help the organization to reach geographically remote publics. The latest stage in the evolution of public relations actually represents "returning the public to public relations" [14, p. 37]. In the case of traditional public relations, the organization mainly focused on the local and regional market, used mass public relations, and there was a time limit and availability during a certain period of time. In addition, traditional PR mostly used one-way communication through traditional channels (television, radio and printed media). It was difficult to evaluate the results of traditional PR [7, p. 250]. Despite the fact that public relations became more interactive with the emergence of new media, an accompanying unwanted problem arose - the difficult identification of "electronic publics" [10, p. 329]. For example, to younger consumers, especially teenagers, TikTok is the most attractive of all social networks [15]. This is the reason that most of the budget for public relations is allocated for the digital PR, that is, social networks. If the organization decides to use social media, it exposes itself to risks in terms of criticism from various interest groups and the public. Such a potential loss of control over communication also puts the organization in an awkward position and, consequently, creates obstacles to establishing good two-way and symmetrical communication. Intensive communication of the organization with external groups through social media makes it difficult to define a unique voice when addressing the public in relation to the various events.

There is a special form of a crisis situation, caused by the rapid spread of messages through social networks, which is called the spillover crises. This type of crisis situation occurs when some external events, related to a certain company, create doubts, concerns or undesirable perceptions about the quality of products or services and other companies belonging to a certain branch of economy [16]. This type of crisis is increasingly occurring in the fashion industry [17]. Organizations in such situations find various ways to supress negative perceptions; for example, by strengthening their identity in relation to the competition, by trying to improve the reputation of the entire industry, etc. Due to spreading the negative publicity through social networks, the organization can fall into a special form of a crisis situation - the so-called paracrisis. Coombs and Holladay define this form of crisis as "a visible situation that can turn into a crisis during which the organization commits unethical or irresponsible behaviour" [18, p. 409]. Although the organization is not exposed to a real crisis - it is not accused of illegal actions - it is still in a situation where interest groups can make demands regarding behaviour change in order to correct immoral or irresponsible actions [11, p. 95]. The trouble is that requests sent through social media have a public character and in that sense represent a threat to the reputation of the organization.

2. PUBLIC RELATIONS AND SOCIAL MEDIA

Technological and social changes, which have significantly transformed aspects of public relations since the 1990s, refer to the perception of the role of the corporation within the global economy, the quality of the environment and the more emphasized role of management in PR. Changes in the domain of communication and the public are of equal importance. Along with the increasingly present proliferation of the public and the weakening of mass media, the modern business is being characterized by the rapid spread of new media technologies and the increasing type of communication with individuals instead of mass audiences. Communication directed towards the user dominates - receiver-driven communication [19, 20]. Instead of the predominance of mass media, characteristic of an industrial society, a global communication network is being established based on mass self-communication in which an individual (1) creates a message, (2) sends it to a potential recipient and (3) independently chooses the content to which the recipient will be exposed [21, p. 55]. This leads to a narrowing of the concepts of receiver and emitter. Since information and communication technologies promote the "dialogue" with the public, it is necessary to include digital PR, consisting of various methods and tools, in all elements of the marketing mix of the company or organization [13, p. 78]. This is, of course, widely applied in the marketing activities of fashion industry companies [22-26].
Bernard Miočić, based on previous research, distinguishes among three roles of public relations: operational-technical, managerial and strategic role [12]. The operational and technical role of PR is reflected in the implementation of communication. The managerial role is not limited only to communication, but also to planning and evaluating communication plans and participating in decision-making processes. The strategic role of PR includes "monitoring the environment, analysing social norms and values, then predicting the consequences of certain phenomena from the environment on strategy and organizational policy, as well as advising top management in relation to these phenomena" [12, p. 38]. Miočić also empirically tested and analysed the application of the model of relations (communication) with the public, with an emphasis on two-way interactive communication and dialogue between organizations and the public. The results obtained from a sample of employees in public relations (n=106) show that the public information model is mostly applied to the Internet (83%), which indicates that the feature offered by the new media environment - interactivity - is not sufficiently appreciated.

3. PUBLIC RELATIONS AND REPUTATION

Analytical research of the organization's interaction with the external environment focuses on three basic categories: corporate identity, corporate image and corporate reputation. Corporate identity is one of the oldest forms of communication between an organization and its target groups. Reputation refers to the reputation that an organization acquires and maintains thanks primarily to good performance, i.e. the use of organizational resources. A good reputation is harder and slower to achieve than a recognizable identity. A

favourable reputation requires more than implementing a formal communication system; a strong identity is needed that is being built by achieving good performance over a relatively longer period of time. Key factors that contribute to a strong reputation include credibility, reliability, transparency, trustworthiness and responsibility. These qualities not only enhance relationships but also establish a solid foundation for long-term success and influence (Figure 1). Restoration of reputation ought to be considered as a part of crisis communication within the wider communication field. Any crisis may present reputational threats to an organization, and, a subsequent process of exchange of messages (caused by a crisis), represents a specific sub-category of communication – crisis communication.

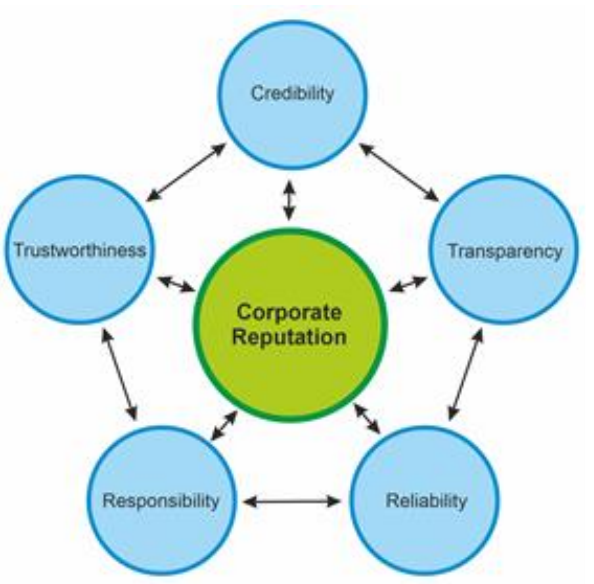

Figure 1: Key factors of a good reputation

Given the nature of the fashion industry, where customer sentiment, brand image, and public perception are crucial, a brand's reputation may be made or broken by how well it handles a crisis. For instance, H&M received a lot of criticism in January 2018 for an advertisement that showed a Black youngster sporting a sweater that read, "Coolest Monkey in the Jungle" (see Fig. 2). The image was widely criticized as racially insensitive and led to protests and calls for a boycott. H&M immediately withdrew the advertisement and issued an apology, acknowledging the mistake and expressing regret for the offense caused. A thorough review of internal processes related to diversity and inclusion was initiated. Meetings were held with representatives of various communities to better understand the issues and improve practices.

Although the incident initially damaged H&M's reputation, the company's transparent and swift response helped mitigate long-term harm. H&M's example demonstrates how timely

response, transparency, and willingness to make changes are crucial in crisis management. Brands that openly acknowledge mistakes, take concrete steps to improve their processes, and actively collaborate with communities can not only mitigate the consequences of crises but also build long-term consumer trust. Furthermore, many fashion industry companies gained a significant experience in terms of communicative strategies during the COVID-19 crisis, that has transformed consumers' relationship with clothes.

Corporate reputation is not easily quantified given that it consists of various dimensions and attributes. However, there are three dominant approaches when it comes to measuring corporate reputation, that is, concepts based on (1) social expectations, (2) "corporate personality" and (3) trust [27]. The essence of the first approach is that people evaluate different aspects of the company's operations based on the expected "behaviour" of the company in the environment (region or country) in which it operates.

Figure 2: The H&M “Coolest monkey in the jungle” advertisement

Corporate relations with the public take place regardless of the marketing function and are aimed at all target groups. Although PR do not represent a typical promotional activity, their ultimate goal, to a large extent, coincides with the goals of other promotional activities [28]. The part of the communication process that refers to the interactions between the organization and certain elements of the environment (first of all, customers and public opinion) is known as customer communication. Customer PR represent the "process of planning, execution and evaluation of public relations programs, which encourage increased procurement and customer satisfaction, through the establishment of

communication (exchange of information and impressions), which identifies companies and their products with needs, desires, concerns and interests of the customers" [29]. The target group of customers is the basic group of customer public relations. The company's activities in communicating with the target public are aimed at informing, persuading and reminding [30, p. 174]. The choice of one of the three objectives, as well as the appropriate communication tactics, is aligned with the phases of the product life cycle, among which are introduction, growth and maturity, then maturity and decline. In the conditions of modern business, when consumers increasingly use social networks (for example, YouTube, Instagram, LinkedIn, X, TikTok, etc.), it is justified to single out connection as a special goal of communication [31, 32]. On the basis of the dominant generation that uses social networks (Table 1), an effective communication strategy can be created. It implies the involvement of the consumer in the capacity of the so-called company representatives who promote the brand through their activities on social networks, and which other participants on these media can perceive as an independent opinion.

Table 1: Main generation in social networks group

Social networks	Established	Country of origins	Approximately consumer	Main generation
LinkedIn	2003	USA	1,1 Billion	Millennials
Facebook	2004	USA	3,1 Billion	Millennials & Gen X
YouTube	2005	USA	2,6 Billion	All
X (ex Twitter)	2006	USA	0,6 Billion	Millennials & Gen Z
Instagram	2010	USA	3 Billion	Gen Z & Millennials
TikTok	2016	P.R.China	2 Billion	Gen Z & Gen Alfa

Source: Authors researching

Promotional activities are aimed at (1) raising awareness, i.e. consumer awareness (cognitive phase), (2) changing consumer attitudes and feelings (emotional phase) and (3) encouraging consumers to a certain type of behaviour (behavioural phase). This order of promotional activities describes well the situation when consumers show interest in certain categories of products. The main goal of customer relations is to urge the consumers to change their state of ignorance to that of making a decision and towards the action of purchasing. The reaction can be expressed in only one way, but it is preferable that the reaction be on three levels of reaction: acquaintance, interest and behaviour [33, p. 169].
According to the AIDA model, there are four desirable responses depending on the means used (Figure 3). The acronym AIDA, created from four words (attention, interest, desire and action), refers to attention (cognitive phase), interest and desire (emotional phase) and action (behavioural phase). There are other ways to gradate consumer reactions, such as

distinguishing five stages of influence on consumers: introduction, interest, evaluation, trial and acceptance [34, p. 225].

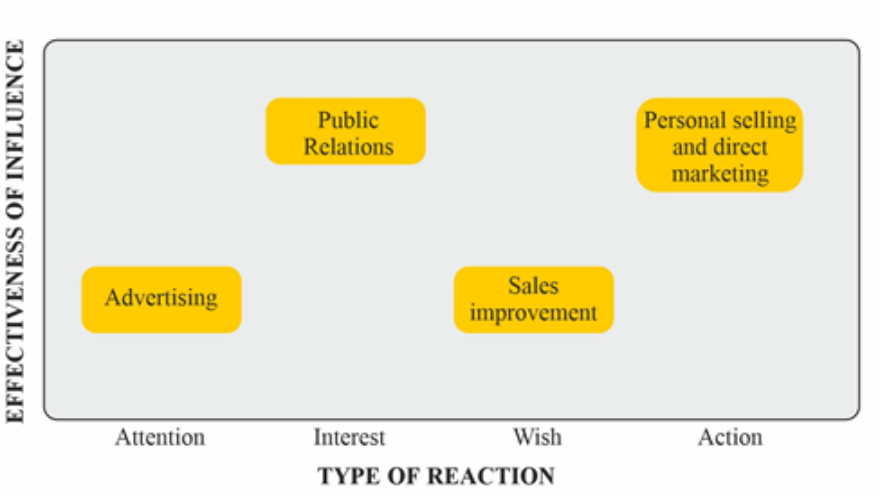

Figure 3: The AIDA model

Communication based on the use of the Internet, i.e. social media such as social networks (for example, Instagram), blogs, forums, websites for the exchange of images and videos (YouTube) is gaining an increasing role in modern business. Interactivity, characteristic of the Internet, has enabled completely new forms of establishing contacts with market participants. The Internet, in fact, gradually developed "from primarily a communication medium, into a sales and/or distribution channel, and finally into a platform for managing relationships with consumers and virtual social communities" [20, p. 147]. Instagram is more popular than other social networks and it is mostly used (61.1%) by users aged 18 to 34 [32, p. 198]. Social media is widely used by the fashion industry for mutual benefit; especially consumers [24-26, 35-37].

Companies rely on three intermediaries to connect with consumers. They can use paid media (including all forms of advertising), acquired media through which consumers, journalists and other interested parties voluntarily express their opinion about the product using "word of mouth" and viral marketing, and their own media, which mostly consist of online marketing communications. The world's most famous fashion brands have greatly developed their own media, which, compared to competing companies, makes it easier for them to access consumers. The company's own website can be very well used as a place where media representatives can get reliable and quality information. It is very common for quality websites to have a special section for journalists, where they have at their disposal complete and updated material needed to create one or more articles, as well as adequate contact addresses for additional information.

4. CONCLUSION

Modern communication technologies are greatly changing the role of public relations in many areas of the economy. Promoting interactive communication is the basic task of public relations, as confirmed by many experiences from the fashion industry.
The Internet represents the omnipresent leader of the so-called communication revolution. One of the greatest advantages of the Internet as a public relations medium is reflected in the possibility of direct and immediate access to a specific target group. This bypasses journalists and traditional news media. At the same time, the Internet is changing the media landscape in communication between organizations and the public.
It can be stated that public relations in the fashion industry represent a process of strategic management by which a fashion brand is carefully built in order to create a positive image of it in the public and maintain strong connections with consumers. In order to fulfil this overall goal, public relations establish and maintain good relations with the media, prepare brand stories, and manage events such as, fashion shows or fairs. The basis of successful public relations, characteristic of the fashion industry, consists of three pillars: communication strategies, crisis management and coordination of various campaigns.

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THE ROLE OF INFLUENCERS IN BUYING LUXURY BRANDS OF WOMEN'S HANDBAGS

Review paper
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***ABSTRACT**: Social networks provide consumers with access to extensive information that influences all stages of the purchasing process, from information search to the purchase itself. The personalization of content, enabled by algorithms and real-time interactions, is a key element that places social networks at the centre of modern marketing. Their potential has also been recognized by fashion influencers, who have become key players between brands and consumers. They play an important role in shaping purchasing decisions themselves, especially for luxury products, because by creating visually appealing content and building relationships with followers, they influence their perception and increase the perceived value and exclusivity of the product.*
The basic purpose of our research was to determine whether exposure to influencers and following their posts increases interest and the likelihood of purchasing a luxury handbag.

***Keywords**: fashion influencers, women luxury handbags, social media.*

ULOGA INFLUENSERA U KUPOVINI LUKSUZNIH BRENDOVA ŽENSKIH TORBI

***APSTRAKT**: Društvene mreže pružaju potrošačima pristup opsežnim informacijama koje utiču na sve faze procesa kupovine, od pretrage informacija do same kupovine. Personalizacija sadržaja, koju omogućavaju algoritmi i interakcije u realnom vremenu, ključni je element koji postavlja društvene mreže u centar modernog marketinga. Njihov potencijal su prepoznali i modni influenseri, koji su postali ključni igrači između brendova i potrošača. Oni igraju važnu ulogu u oblikovanju samih odluka o kupovini, posebno za luksuzne proizvode, jer kreiranjem vizuelno privlačnog sadržaja i izgradnjom odnosa sa pratiocima utiču na njihovu percepciju i povećavaju percipiranu vrednost i ekskluzivnost proizvoda. Osnovni cilj našeg istraživanja bio je da utvrdimo da li izloženost influenserima i praćenje njihovih objava povećava interesovanje i verovatnoću kupovine luksuzne torbe.*

***Ključne reči:** modni influenseri, luksuzne ženske torbe, društvene mreže.*

1. INTRODUCTION

The luxury handbag market is constantly evolving, reflecting dynamic trends shaped by consumer behavior, technological innovation, and cultural shifts. Trends not only define the aesthetics and functionality of handbags but also influence the very strategies of global luxury brands. Understanding trends is key to understanding the broader development of the luxury fashion industry [1].

Luxury handbags are more than just fashion accessories. They represent a combination of superior craftsmanship, innovative technology and personal expression. They combine functionality and aesthetics, which also reflect the cultural dynamics of today. In the future, they will also symbolize personal stories, social trends and various technological advances, while also reflecting changing social needs and consumer values.

In this paper, we presented, defined and analysed the field of social media and influencers in relation to luxury handbag brands.

2. FASHION INFLUENCERS

Fashion has always been a dynamic reflection of cultural shifts, societal values, and personal expression. For decades, magazines, designers, and celebrities dictated what was considered “in style”. However, with the rise of social media, the fashion landscape has changed dramatically.

The change toward a more sustainable fashion system requires efforts from multiple actors across the fashion market, from fashion designers, brands and retailers to consumers, but also policymakers or fashion associations [2].

Influencers are every day, ordinary Internet users who accumulate a relatively large following on blogs and social media through the textual and visual narration of their personal lives and lifestyles, engage with their following in digital and physical spaces, and monetize their following by integrating “advertorials” into their blog or social media posts [3].

Influencers are winning, their popularity has taken off, and they reach more followers every day. It is impossible to open your Instagram page without seeing at least one Fashion Instagram influencer, they are taking Instagram and influencing to a whole new level and they know exactly what they are doing. They have a strong connection with their millions of followers, their perfect outfits and their perfect lives, and it feels like they are your best friend, the one you go to when you need advice [4].

Social media platforms like YouTube, Instagram, and later TikTok have transformed how people share and consume information since the early 2000s. With the democratisation of content creation, it seemed that anyone with a smartphone could establish a personal brand, showcase their distinct aesthetic, and attract followers from around the world. This shift gave rise to a new class of trend-setters: influencers.

Fashion influencers gained large followings by sharing photos of their everyday outfits, offering style advice, and providing intimate glimpses into their personal lives. Their relatability and approachability set them apart from traditional celebrities, helping them

forge a closer bond with their audience. As their fan bases grew, brands took notice and began to collaborate with them [5].
Influencers also play a key role in shaping brand identity itself, by humanizing companies, providing a face and personality that audiences can relate to. This relationship-building is crucial in an era where consumers increasingly prioritize authenticity and transparency from the brands they support [6].
To maximize their potential, companies must prioritize ethical practices, ensure transparency in partnerships with influencers, and align collaboration with their brand values and the interests of their target audience [7].
A fashion influencer is a social media personality with a large following who primarily creates fashion-related content and has the ability to influence the opinions and purchasing behaviours of others through their recommendations [8]. Followers typically closely observe the influencer's activities, including their style and product recommendations.

3. WOMEN'S LUXURY FASHION HANDBAGS

Over the past century, the development of luxury women's handbags has been closely linked to broader social, cultural and economic changes, making them not just functional accessories, but powerful symbols of status, identity and personal expression [9].
In recent years, the luxury handbag industry has undergone dynamic changes that reflect broader shifts in fashion, consumer behaviour, and cultural values. Handbags, no longer just functional accessories, have evolved into powerful symbols of status, self-expression, and identity. Several key factors are influencing modern luxury handbag trends, including technological innovation, sustainability, celebrity and influencer endorsements, and a renewed focus on craftsmanship and exclusivity. Social media platforms such as Instagram and TikTok have had a major impact on consumer preferences, with fashion influencers and celebrities often showcasing the latest handbag styles, driving demand and shaping trends. In addition to aesthetics, consumers are increasingly valuing ethical considerations, which is driving luxury brands to adopt more sustainable and eco-conscious production methods. Leather alternatives, eco-friendly materials, and transparency in the supply chain are becoming as important as the design and heritage of the brand itself. Additionally, personalization and limited editions are on the rise as customers seek unique pieces that reflect their personal style and individuality [10].

4. EMPIRICAL FINDINGS

We prepared a completely anonymous and short survey questionnaire on the web portal www.1ka.si. We chose a target population where we focused only on women. 58 women participated in the survey, of which 50 women answered the survey in full. The link to the online questionnaire was shared via online social platform Instagram.
First, we wanted to know the age of the respondents.

Table 1: Age of the respondents

Age (years)	Frequency	Percent
18-24	14	28 %
25-34	25	50 %
35-44	9	18%
45 -54	1	2%
55 and more	1	2%
Total	50	100%

The table 1 shows that 25 people belong to the age group between 25 and 34 years, which represents 50%. 14 people or 28% of the respondents belong to the age group between 18 and 24 years. 9 respondents belong to the age group between 35 and 44 years, which represents 18%. There is only one respondent in the age groups between 45 and 54 years and 55 years or more, so for each group this amounts to 2%.
Then we were interested in which social networks the respondents use most often.

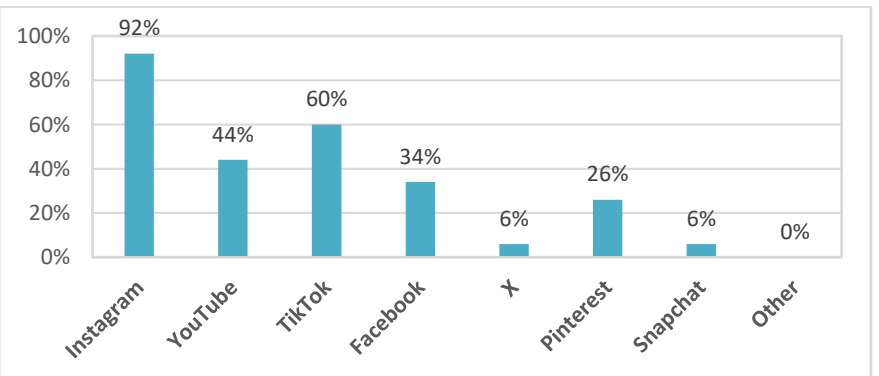

Figure 1: Most used social networks

The figure 1 shows that 46 respondents, which is 92%, use the social network Instagram the most. The second most used social network is TikTok, which is used by 30 respondents. which represents 60%. In third place is YouTube, which is used by 22 respondents (44%). It is followed by Facebook, which is used by 17 respondents, which is 34%. Pinterest is used by 13 respondents (26%), and X and Snapchat are used by only 3 people (6%). We also added the option for respondents to give another answer to the question, which they did not do in this case.

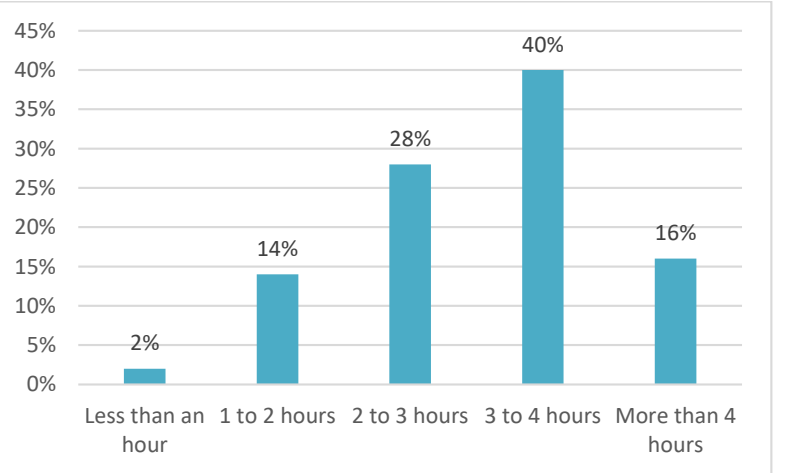

Figure 2: Time spent on social media

For this question, we were interested in how much time respondents spend on social networks. We found that 20 respondents spend 3 to 4 hours a day on social networks, which represents 40%. 154 respondents (28%) spend 2 to 3 hours on social networks, and 8 respondents (16%) spend more than 4 hours. 7 respondents (14%) use social networks only 1 to 2 hours a day and only one respondent (2%) uses them less than an hour a day (Fig 2). In the next question, we asked respondents how often they follow influencers on social media (Figure 3).

Most respondents (22), representing 44%, follow influencers on social media daily. 17 respondents (34%) follow them several times a day, and 8 respondents (16%) follow them weekly. Only two respondents (4%) follow them monthly and only one (2%) follows them rarely. No respondent answered that they never follow influencers on social media.

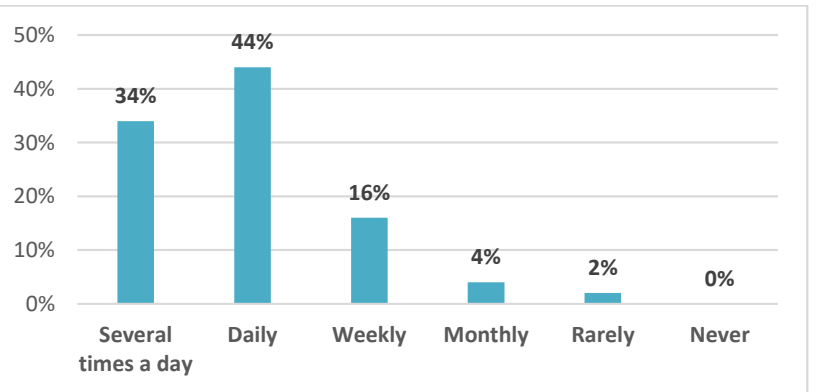

Figure 3: Influencers on social media

The next question asked us how many influencers the respondents follow on social media.

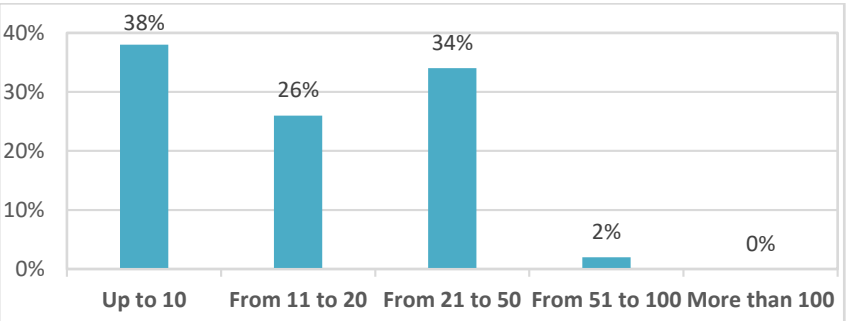

Figure 4: The number of influencers they follow

Most respondents follow up to 10 influencers, representing 38%. 17 respondents (34%) follow 21 to 50 influencers, and 13 respondents (26%) follow 11 to 20 influencers. Only one respondent (2%) follows 51 to 100 influencers, and none follows more than 100 influencers (Figure 4).

Then we were interested in what type of influencers the respondents follow, i.e. what kind of content they publish (Figure 5).

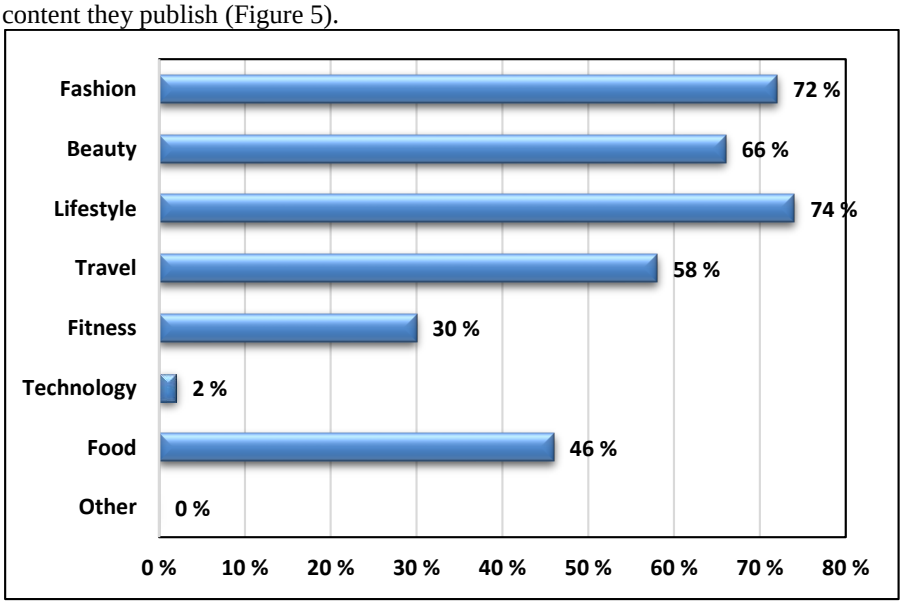

Figure 5: Types of influencers they follow

The most respondents follow influencers with lifestyle content, 37 of them, representing 74%. They are followed by fashion influencers, followed by 36 respondents (72%). In third

place are influencers who post content about beauty, followed by 33 respondents (66%). Influencers who post content about travel are followed by 29 respondents, representing 58%. They are followed by influencers with food content, followed by 23 respondents (46%). Influencers with fitness content are followed by 15 respondents (30%), and influencers with technology content are followed by only 1 respondent (2%). None of the respondents answered the answer with the option "other".

We were also interested in how often respondents see content about luxury handbags on their social networks. Most respondents, 18, see them on their networks weekly, which represents 36%. 16 respondents see them daily, which represents 32%. 6 respondents rarely see them (12%). 3 respondents answered several times a day, monthly, and never, each answer representing 6% (Figure 6).

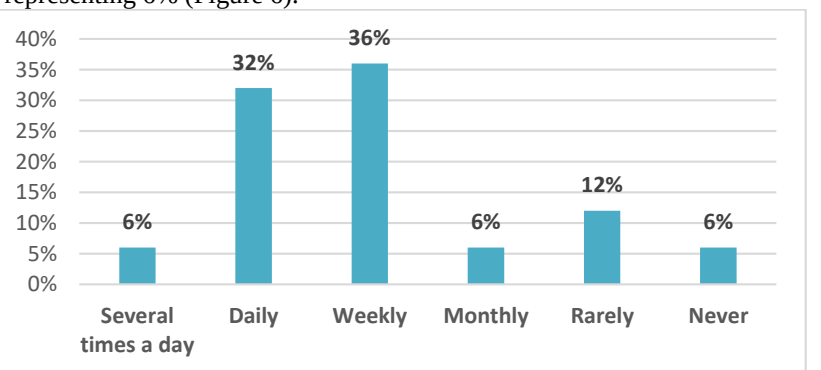

Figure 6: Frequency of seeing content about luxury handbags on social media

The last question asked us how likely it is to buy a luxury handbag based on an influencer's recommendation. 15 respondents, representing 30%, would likely buy a luxury handbag based on an influencer's recommendation. 13 respondents, representing 26%, are unlikely to buy a handbag based on an influencer's recommendation. 12 respondents (24%) are neutral about the decision. 9 respondents (18%) are very unlikely to buy a handbag based on an influencer's recommendation. 2 respondents, representing 4%, are very likely to follow the recommendations (Figure 7).

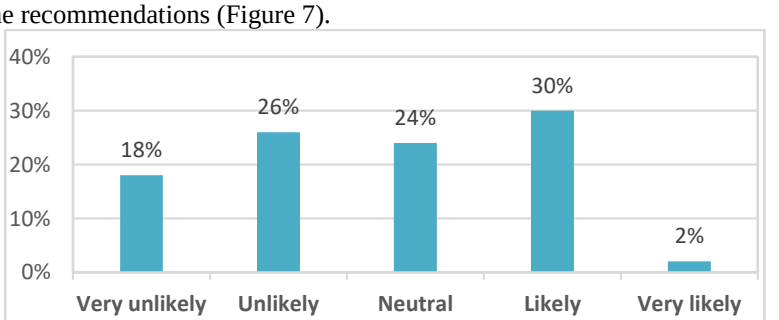

Figure 7: Probability of purchasing a luxury handbag after being recommended by an influencer

5. CONCLUSION

Influencers and social media have fundamentally transformed the way brands communicate with consumers over the past two decades, helping to change consumer culture and fashion trends. The transition to the digital age and the development of Web 2.0 have enabled the rise of platforms such as Instagram, YouTube and TikTok, where influencers reach millions of followers around the world with their content. They have become key intermediaries between brands and consumers, creating long-term relationships that go beyond traditional forms of advertising.

The fashion sector is one of the most important areas where influencers play a key role in spreading trends and shaping various cultural norms. Modern social media platforms have democratized fashion, allowing everyday individuals to share their personal style, set trends and influence their audiences. Fashion influencers have proven through their successful careers that it is possible to build strong personal brands that go beyond simply promoting products.

The success of influencers in the modern digital age is determined by authenticity, credibility and adaptability. Consumers, especially millennials and Generation Z, value the direct communication that influencers offer, which makes their decisions more thoughtful and personally relevant. They have become key players in modern marketing and culture, as they shape consumer preferences and behavioural patterns with their content. With their role, they are not just a tool for promotion but have become important players shaping the future of consumer culture.

Through research, we found that influencers have a positive impact on the purchase of luxury women's handbags, as well as that greater exposure to influencers is positively associated with increased interest in purchasing luxury handbags. The development of luxury handbags throughout history has reflected broader social, cultural and technological changes that have shaped women's lifestyles and attitudes towards fashion.

With their authenticity and carefully curated content, they successfully build trust and thus influence consumer behaviour. Their recommendations are based on personal experience, and through their connection with followers, they influence the perception of luxury products themselves, making them more desirable in the eyes of consumers. Frequent contact with content increases awareness of luxury brands and stimulates desire for them. Consumers who follow social media posts and follow fashion trends are looking for ways to imitate, which only increases the desire to purchase luxury handbags, as they perceive them as a status symbol and exclusivity. Influencers with a larger number of followers reach a wider audience, but of course it is not a key factor in the purchase decision.

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9. Međunarodna naučna konferencija
*„**Savremeni trendovi i inovacije u tekstilnoj industriji**“*
17-18. septembar 2026. Beograd, Srbija

AI-POWERED BODY SIZE MATCHING: A NEW PARADIGM FOR MICRO-INFLUENCER MARKETING IN FASHION E-COMMERCE

Professional paper
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ABSTRACT: *Online shopping has become one of the most widely adopted consumption practices, offering undeniable convenience to consumers. At this stage, the critical challenge for retailers is no longer expanding access to online channels, but rather enhancing customer loyalty and delivering an optimal shopping experience. This challenge is particularly prominent in the fashion e-commerce sector, where the absence of physical interaction and the subjective nature of garment fit significantly affect consumer satisfaction.. Failure to find the appropriate fit or meet consumer expectations results in high return rates, creating additional costs and logistical burdens for both consumers and sellers. This study presents an innovative solution for the online marketing of apparel by introducing a body-matching algorithm that brings together individuals with similar body types within a dedicated mobile application platform. The developed system (ModaApp) enables users to match with others who share similar morphological characteristics, allowing them to observe how a garment fits on a "similar body double" and benefit from peer experiences before purchase. Furthermore, the study provides a robust infrastructure for micro-influencer marketing, allowing users to earn commissions through their shared experiences. Consequently, this model aims to minimize return-related issues in online apparel shopping, enhance the decision-making process, and foster a more sustainable e-commerce ecosystem.*

Keywords: *Body Matching Algorithm, Fashion E-commerce, Micro-influencer marketing, Virtual Fit, Sustainable Consumption.*

USKLAĐIVANJE VELIČINE TELA POKRENUTO VEŠTAČKOM INTELIGENCIJOM: NOVA PARADIGMA ZA MARKETING MIKRO-UTICAJNIH KLIENTA U MODNOJ E-TRGOVINI

APSTRAKT: *Kupovina preko interneta postala je jedna od najšire usvojenih praksi potrošnje, nudeći neospornu pogodnost potrošačima. U ovoj fazi, ključni izazov za trgovce više nije proširivanje pristupa onlajn kanalima, već povećanje lojalnosti kupaca i pružanje optimalnog iskustva kupovine. Ovaj izazov je posebno izražen u sektoru modne e-trgovine, gde odsustvo fizičke interakcije i subjektivna priroda kroja odeće značajno utiču na zadovoljstvo potrošača. Neuspeh u pronalaženju odgovarajućeg kroja ili ispunjavanju očekivanja potrošača rezultira visokim stopama povrata, stvarajući dodatne troškove i logistička opterećenja i za potrošače i za prodavce. Ova studija predstavlja inovativno rešenje za onlajn marketing odeće uvođenjem algoritma za uparivanje tela koji okuplja pojedince sa sličnim tipovima tela unutar namenske platforme mobilnih aplikacija. Razvijeni sistem (ModaApp) omogućava korisnicima da se uparuju sa drugima koji dele slične morfološke karakteristike, omogućavajući im da posmatraju kako odeća stoji na „sličnom dvojniku tela“ i da imaju koristi od iskustava vršnjaka pre kupovine. Štaviše, studija pruža robusnu infrastrukturu za mikro-influenser marketing, omogućavajući korisnicima da zarađuju provizije kroz svoja zajednička iskustva. Shodno tome, ovaj model ima za cilj da minimizira probleme vezane za povraćaj robe prilikom kupovine odeće putem interneta, poboljša proces donošenja odluka i podstakne održiviji ekosistem e-trgovine.*

Ključne reči: *Algoritam za podudaranje tela, modna e-trgovina, mikro-influenser marketing, virtuelna forma, održiva potrošnja.*

1. INTRODUCTION

The rapid development of digital technologies and the ease of access to online platforms have transformed e-commerce from an alternative channel into a dominant sector. Despite its advantages in attracting and engaging consumers, the lack of physical interaction remains an unresolved challenge in this environment. This issue is particularly critical in online apparel shopping, where the usability and satisfaction associated with purchased products are directly linked to how well they meet consumer expectations. The gap between experiencing a physical product and evaluating it in a virtual environment continues to be a significant barrier. As a result, unsuitable garments are frequently returned, leading to additional costs and time burdens for both consumers and retailers.
The return of online purchases should be evaluated from both the retailer's and the consumer's perspectives. Recent reports indicate that overall e-commerce return rates reached approximately 20% in 2024, marking one of the highest levels recorded [1]. These high return rates are influenced by several factors, including easy return policies and free return options, which have become standard practices in e-commerce. However, the issue is particularly pronounced in the apparel sector, where return rates can reach up to 40%, the highest among all product categories. In clothing retail, returns are primarily driven by size inconsistencies across brands and poor fit. In addition, consumers—especially Generation Z shoppers—often purchase multiple sizes of the same item with the intention of returning those that do not fit. Studies show that the most common reasons for returns

include sizing issues, dissatisfaction with the product, and discrepancies between the product description and the actual item [2].These findings highlight a critical gap between the digital representation of garments and their real-world physical experience. This disconnect creates a significant barrier to informed purchasing decisions. Consequently, poor-fitting or unsatisfactory apparel leads to high return rates, imposing substantial logistical costs and time burdens on both consumers and retailers.

To enhance the interaction between online apparel products and consumers, various approaches have been proposed in the literature. Particularly, solutions addressing size and fit issues have attracted significant attention. For instance, Nasibov et al [3]. introduced a method that recommends appropriate garment sizes based on body measurements calculated using fuzzy logic. However, this approach requires precise body measurements for both the consumer and the product, which limits its practicality in real-world applications. Beside, current literature presents several distinct technological approaches to solving the online apparel fit problem, ranging from article-centric Bayesian models like SizeFlags, which leverage noisy return data to identify problematic article behavior [4,5,] to machine learning frameworks that predict shirt and pant sizes with high accuracy based on basic metrics like height, weight, and BMI [6,7.]Other systems utilize standardized mapping,o extract user sizes and compare them against "coded" garment data [8,9], or personalized recommendation services which find fit similarities between a user's past successful purchases and new items across different brands [10,11.]While Virtual Fitting Room (VFR) and Augmented Reality (AR) solutions allow for 3D visualization, they are often limited by consumer privacy concerns and "unrealistic mapping" caused by graphical glitches in texture and positioning [12].

The proposed system, which matches consumers with similar body types, is considered superior because it addresses the inherently personal and subjective nature of garment fit, which is often not effectively captured by standardized national datasets and rigid algorithmic approaches.By utilizing real consumer data from individuals with similar body profiles, the system overcomes two major limitations of existing solutions: the “unrealistic matching” problem commonly found in avatar-based systems, and the “cold start” problem associated with new products that lack sufficient purchase history.Furthermore, the system directly targets the lack of physical experience, which is one of the primary drivers of the approximately 40% return rate in the apparel sector. It achieves this by enabling users to observe how garments appear on individuals with similar body types, while also providing direct access to user-generated feedback and reviews related to the product.

2. MATERIALS AND METHODS

The proposed system, ModaApp, shifts the focus from traditional garment-to-body measurement comparisons to a peer-to-peer "body similarity" model. The core objective of this methodology is to simplify data collection while enhancing the accuracy of visual fit perception through real-human data.

2.1. Data Acquisition and User Profiling

Instead of requiring professional-grade anthropometric measurements, the system utilizes a streamlined four-point data entry process to define a user's morphological profile. To access and categorize consumer data, the platform prompts users with four strategic questions: *Weight,Height,Upper Body Size (Based on recent purchases),Lower Body Size (Based on recent purchases)*

To refine the matching accuracy beyond standard S/M/L/XL labels, the system incorporates a "double-reference" check for sizing. For instance, a user who typically wears a 'Large' is asked to select their second most frequent size (e.g., L and XL or L and Medium). This approach allows the algorithm to identify the "size-edge" of the consumer. By determining whether a user leans toward a larger or smaller fit within a specific size category, the system achieves a more granular similarity mapping between users.

2.2 Peer-to-Peer Matching Mechanism

The algorithm processes these four parameters to find "body doubles" within the database with Euclidean distances and weight function in given Formula 1.

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$$d(x,y) = \sqrt{\sum_{i=1}^{n} wi\ (xi - yi)^2} \qquad (1)$$

In thee case of propesed system, each user registered anddata of the suer is collected as;

x=(height, weight, upper size, lower size)

Weighted Euclidean distance is employed to measure similarity between users' body profiles by assigning different importance levels to each anthropometric feature. While traditional distance measurements often assume that each physical attribute contributes equally to the similarity score, this approach frequently fails to represent complex body morphologies accurately. To overcome this limitation, a neural network architecture was designed to dynamically determine the discriminative power of each attribute, optimizing the coefficients within the weighted Euclidean formula during the learning processThis allows the model to better capture the subjective nature of garment fit and improve matching accuracy in fashion recommendation systems.The predictive performance of the developed model was evaluated using Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE) metrics. The results show that the neural network successfully learns appropriate weights with low error and stable performance. In particular, the low MAPE values indicate that the model maintains consistent accuracy across different body data ranges. Overall, the findings demonstrate that the proposed hybrid approach, combining neural networks with weighted Euclidean distance, provides more accurate and reliable body matching compared to traditional.

3. IMPLEMENTATION OF THE MOBILE PLATFORM

3.1. System Architecture and User Interface

The architecture of the mobile platform is designed to facilitate a seamless flow from raw data entry to a personalized social commerce experience. The system operates through a three-stage integration: data acquisition, algorithmic processing, and visual interaction.

User Profiling and Data Entry: Upon registration, the application initiates a streamlined onboarding process. Users are required to complete a simplified morphological form that includes gender, height, and weight.

Dynamic Similarity Algorithm: The backend engine utilizes a real-time similarity algorithm. Unlike static models, this algorithm performs a re-calculation every time a new user is added to the database. It computes a "similarity ratio" by comparing the morphological profiles of the target user against the existing database. This ensures that the proximity mapping remains precise and evolves as the community grows.

Interactive Social Interface: The UI/UX is centered around a personalized "Similarity Feed." In the profile and discovery screens, users interact with posts shared by their "body doubles." Each post contains several high-value data points:

Similarity Ratio: A percentage indicating how closely the creator’s body type matches the viewer's profile.

Garment Metadata: Detailed information regarding the size and fit of the clothing shown.

Peer Insights: Qualitative comments from the creator about the garment's texture, stretch, and real-world comfort.

Direct Commerce Link: An integrated link that redirects the user to the retailer’s website for an informedpurchase. (Figure 1)

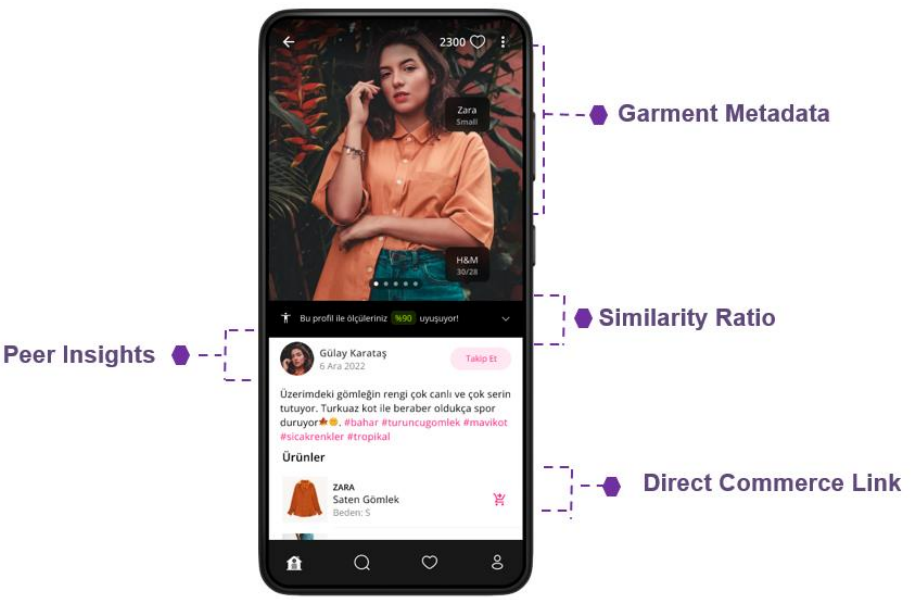

Figure 1: Image from ModaApp

4. CONCLUSION

The development of the proposed mobile platform has been successfully completed, and it is currently in its active operational phase. While the quantitative longitudinal data regarding long-term consumer behavior is still being collected, the structural impact of the system allows for an informed discussion on its potential outcomes.The primary result of the implementation is the successful elimination of the "visualization barrier." By allowing users to observe desired apparel on "body doubles" with high similarity ratios, the system provides a proxy for the physical trial room experience. By minimizing "sizing inaccuracies" and "aesthetic mismatch"—the two leading drivers of returns—the platform is expected to reduce the logistical footprint of e-commerce. This reduction directly contributes to the sustainability of the fashion industry by lowering the carbon emissions associated with reverse logistics.The platform is currently running in a live environment. Detailed statistical analysis regarding the exact reduction in return rates, conversion rate optimizations, and user retention metrics are under continuous monitoring.

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GREEN BONDS AS AN INSTRUMENT OF SUSTAINABLE TRANSFORMATION IN THE TEXTILE INDUSTRY

Professional paper
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ABSTRACT: *The textile industry is one of the most significant sectors of the global economy, yet it is also one of the largest generators of negative environmental externalities, including greenhouse gas emissions, intensive resource consumption, and waste accumulation. In the context of accelerating climate change and the transition toward sustainable economic models, sustainable finance is gaining strategic importance, with green bonds emerging as one of the key instruments for mobilizing capital toward environmentally sustainable projects. This paper aims to provide a comprehensive analysis of the role of green bonds in financing the sustainable transformation of the textile industry by integrating the theoretical framework of sustainable finance, analyzing market trends, and evaluating empirical evidence. The methodological approach includes the analysis of secondary data, comparative analysis of financial instruments, and case studies of relevant market actors. The research findings indicate that green bonds contribute to improving capital allocation toward projects that support decarbonization, circular economy practices, and more efficient resource management within the textile sector. However, their effectiveness largely depends on an appropriate regulatory framework, the level of transparency, standardization of reporting, and the integration of ESG criteria into investment processes.*

Keywords: *green bonds, textile industry, ESG, sustainable finance, circular economy.*

ZELENE OBVEZNICE KAO INSTRUMENT ODRŽIVE TRANSFORMACIJE TEKSTILNE INDUSTRIJE

APSTRAKT: *Tekstilna industrija predstavlja jedan od najznačajnijih sektora globalne privrede, ali istovremeno i jednog od najvećih generatora negativnih eksternalija po životnu sredinu, uključujući emisije gasova sa efektom staklene bašte, intenzivnu potrošnju resursa i akumulaciju otpada. U kontekstu ubrzanih klimatskih promena i tranzicije ka održivim ekonomskim modelima, održivo finansiranje dobija strateški značaj, pri čemu green bonds predstavljaju jedan od ključnih instrumenata za mobilizaciju kapitala usmerenog ka ekološki održivim projektima. Cilj ovog rada je da pruži sveobuhvatnu analizu uloge zelenih obveznica u finansiranju održive transformacije tekstilne industrije,*

kroz integraciju teorijskog okvira održivog finansiranja, analizu tržišnih trendova i evaluaciju empirijskih primera. Metodološki pristup obuhvata analizu sekundarnih podataka, komparativnu analizu finansijskih instrumenata i studije slučaja relevantnih tržišnih aktera. Rezultati istraživanja ukazuju da zelene obveznice doprinose unapređenju alokacije kapitala ka projektima koji podržavaju dekarbonizaciju, cirkularnu ekonomiju i efikasnije upravljanje resursima u tekstilnom sektoru. Ipak, njihova efektivnost u velikoj meri zavisi od adekvatnog regulatornog okvira, nivoa transparentnosti, standardizacije izveštavanja i integracije ESG criteria u investicione procese.

Ključne reči: *zelene obveznice, tekstilna industrija, ESG, održivo finansiranje, cirkularna ekonomija.*

1. INTRODUCTION

The contemporary textile and fashion industry stands at a critical crossroads. On one hand, it represents a significant economic sector that employs millions of people worldwide and drives global supply chains. On the other hand, it creates profound ecological and social challenges that can no longer be ignored. According to UNEP [16] data, this sector is responsible for 2–8% of global greenhouse gas emissions, consumes an astonishing 215 billion liters of fresh water annually (equivalent to the volume of approximately 86 million Olympic-sized swimming pools), and generates around 92 million tons of textile waste each year — the equivalent of a full truckload of clothing being dumped in a landfill or incinerated every second. Fast fashion further exacerbates the situation. Clothing production doubled between 2000 and 2015, while the average lifespan of a garment decreased by as much as 36%. The result is excessive resource consumption, massive pollution of water bodies with chemicals and microplastics, and growing social pressures in supply chains, particularly in developing countries.

In this context, traditional financing models show clear limitations. Bank loans are often too rigid for long-term green investments that require substantial changes across the entire value chain, while public funds are far from sufficient to cover the enormous costs of the necessary transition. This is where green bonds come into play — long-term debt instruments whose proceeds are used exclusively for projects with a clear positive environmental impact. They not only provide companies with access to capital under more favorable terms but also send a strong signal to the market and consumers about a serious commitment to sustainability.

This paper examines the potential of green bonds as an instrument for accelerating the sustainable transformation of the textile industry. Particular emphasis is placed on the European regulatory framework (the European Green Deal and the Strategy for Sustainable and Circular Textiles) and the implications for the Western Balkan countries, including Serbia. The structure of the paper includes the theoretical framework of sustainable finance, an analysis of regulatory conditions, empirical examples of successful issuances, identification of key challenges, and practical recommendations for application in the regional context.

2. THEORETICAL FRAMEWORK AND MECHANISM OF GREEN BONDS

Green bonds are defined and governed by the Green Bond Principles of the International Capital Market Association (ICMA). These principles represent a voluntary framework that has become the de facto gold standard in the field of green finance. They rest on four key pillars: clear use of proceeds, a rigorous process for project evaluation and selection, transparent management of funds throughout the life of the bond, and regular, detailed reporting on achieved results. Unlike ordinary (conventional) bonds, green bonds require transparent monitoring of the actual environmental impact of the projects they finance — the so-called impact reporting. This means that the issuer cannot simply raise funds and spend them at its own discretion; it must clearly demonstrate to investors what has been concretely achieved in terms of emission reductions, water savings, recycling, or other measurable environmental benefits. In recent years, a significant evolution of this instrument has emerged — the so-called sustainability-linked bonds (SLB). Unlike classical green bonds, the coupon rate (interest) on these bonds is directly linked to the achievement of pre-agreed ESG targets. If the targets are not met, the interest rate increases, creating a strong financial incentive for real change. Examples of such targets include reducing Scope 3 emissions in the supply chain, increasing the share of recycled materials in production, or reducing water consumption per unit of product. These instruments are particularly useful for the textile industry, as they enable financing of a wide range of measures across the entire, highly complex value chain — from cotton cultivation and fiber production, through processing and sewing, to product design and end-of-life recycling systems. In this way, they overcome the limitations of classical green bonds, which are often focused only on specific, easily measurable projects.
In the domestic literature, Vićentijević (2018) [17] highlights the accounting aspects of the circular economy in the textile industry, emphasizing the need to adapt financial reporting to new sustainability models. Similarly, Vićentijević et al. (2022) [19] analyze the integration of CSR and SDGs in creating added value in the textile industry, providing an important foundation for understanding the role of financial instruments in this transition.
In the domestic literature, Vićentijević (2018) highlights the accounting aspects of the circular economy in the textile industry, emphasizing the need to adapt financial reporting to new sustainability models. Similarly, Vićentijević et al. (2022) analyze the integration of CSR and SDGs in creating added value in the textile industry, providing an important foundation for understanding the role of financial instruments in this transition.

3. REGULATORY CONTEXT IN THE EUROPEAN UNION

The European Green Deal, presented in 2019, represents the European Union’s ambitious strategic framework for achieving climate neutrality by 2050. Within this broader package, the Strategy for Sustainable and Circular Textiles from March 2022 occupies a central place regarding the textile sector. This strategy aims to fundamentally change the way textiles are produced, used, and disposed of, shifting the focus from the linear “take-make-dispose” model to a genuine circular economy. Among the key measures envisaged by the

Strategy are: the introduction of ecodesign (mandatory requirements for durability, recyclability, and repairability of products), extended producer responsibility (EPR), the Digital Product Passport (DPP) as a tool for greater transparency throughout the product lifecycle, and a ban on the destruction of unsold or returned textiles. These regulations are not only environmental in nature — they directly affect the financial side of business. Companies that fail to adapt to the new rules face higher capital costs, restricted access to the EU market, and increasing risks of regulatory penalties. In such an environment, green bonds and similar sustainable finance instruments can serve as an important bridge between strict regulatory requirements and real business needs. They enable companies to raise the necessary capital for concrete investments — from switching to renewable energy sources in factories, to establishing recycling and reuse systems, to improving the monitoring and optimization of complex supply chains. The Digital Product Passport plays a particularly important role in this process. Vićentijević and Simeunović (2024) [18] emphasize that the DPP can significantly contribute to improving the sustainability of the textile industry and the circular economy, primarily through increased transparency and easier monitoring of environmental performance. Similar observations can be found in other authors: Papile and Del Curto (2025) [14] highlight the importance of the DPP for integrating information on raw materials in the textile ecosystem, while Legardeur and Ospital (2024) [13], in a study for the European Parliament, analyze the practical possibilities of implementing the digital passport in the textile sector and its potential to accelerate circular practices. In this way, green bonds not only help finance the necessary changes but also enable companies to respond systematically to growing regulatory and market demands.

4. EMPIRICAL EXAMPLES AND CASE STUDIES

One of the most significant examples of the application of this instrument in the textile industry is undoubtedly the H&M Group. In February 2021, the company issued sustainability-linked bonds worth €500 million with a maturity of 8.5 years. The bonds were directly linked to three key sustainability targets: increasing the share of recycled materials to 30% by 2025, reducing emissions from own operations by 20%, and reducing absolute emissions across the value chain. Investor interest was exceptionally high — the bonds were oversubscribed nearly eight times, clearly demonstrating market confidence in the seriousness of their green strategy.

Similar experiences have been recorded by other well-known companies in the sector. Luxury giant Chanel issued two tranches of sustainability-linked bonds in 2020 totaling €600 million, with targets to reduce emissions in own operations by 50% by 2030 and by 10% in the supply chain. Burberry has also successfully placed green bonds, while Adidas has attracted significant investor attention with its issuances focused on emission reductions and the transition to sustainable materials. In recent years, an increasing number of companies from Asia and Europe, including some smaller players supported by funds such as the Good Fashion Fund, have been using these instruments to finance concrete projects such as factory modernization and the introduction of circular processes.

These examples clearly show that green and sustainability-linked bonds bring multiple benefits. They serve not only as a source of capital for necessary investments but also significantly strengthen the company's reputation in the market, facilitate cooperation with suppliers, and enable participation in programs such as the Green Fashion Initiative or the Fashion Pact. At the same time, the success of these issuances has most often been recorded among large, publicly listed companies that have the resources for certification and transparent reporting.

However, for small and medium-sized enterprises that dominate the textile sector in the Western Balkans, the situation is considerably more complex. High issuance costs, complex verification requirements, and a lack of expertise represent serious obstacles. [1,2,3,4,8,9].

5. CHALLENGES AND LIMITATIONS

Despite its great potential, the application of green bonds in the textile industry faces numerous serious challenges that limit their wider use. The most frequently mentioned problem is greenwashing. When verification and control are not sufficiently strict, companies can easily present their activities as much greener than they actually are. In this way, raised funds are sometimes used for projects with very limited or even questionable real environmental impact. According to some studies, as many as one-third of corporate green bond issuers show poorer environmental performance after issuance (Hong Kong Monetary Authority, 2022)[10]. Another significant problem is the high fragmentation of the sector. The textile industry is characterized by the dominance of small and medium-sized enterprises, especially in Asia and the Western Balkan countries. These enterprises often lack sufficient capacity to scale green projects, while complex supply chains further complicate implementation and monitoring. A particularly demanding challenge is the lack of standardized metrics for measuring Scope 3 emissions, which account for the largest part of the total carbon footprint of textile companies. Without reliable and widely accepted measurement methods, it is difficult to set realistic targets and later prove their achievement to investors. High costs of issuance and continuous reporting should also be added. The process of certification, engagement of external auditors, and preparation of detailed impact reports can be extremely expensive and administratively demanding, making it unprofitable for smaller market players.

In the context of Serbia and the Western Balkan region, these challenges are even more pronounced. An underdeveloped capital market, limited availability of guarantee funds, and insufficient state incentives for green projects further hinder access to these instruments.

6. CONCLUSION

Green bonds are proving to be a highly promising financial instrument that can significantly accelerate the sustainable transformation of the textile industry. They enable the raising of necessary capital while simultaneously sending a clear message to investors,

partners, and consumers that the company is seriously addressing issues of circularity and reducing environmental impact. They achieve the best results when combined with public-private partnerships and expert technical support. However, in order to fully realize their potential, concrete and systemic changes are required. Based on the analysis, the following key recommendations stand out: Develop targeted national incentives and guarantee funds specifically aimed at small and medium-sized enterprises, as they form the backbone of the textile sector in Serbia and the region, while facing the greatest barriers to accessing such instruments. Subsidies, guarantees, or tax reliefs would be of great importance. Strengthen the capacities of enterprises for ESG reporting and certification through trainings, mentoring programs, and expert support. Without quality data and transparent reporting, it is difficult to gain investor confidence. More actively encourage regional cooperation and knowledge exchange with European Union countries, using available funds to transfer best practices and experiences. Integrate green financial instruments into national strategies for the development of the circular economy, so that green bonds are not an isolated measure but part of a broader and coherent policy framework. In addition, it would be worthwhile to develop hybrid financing models that combine bonds with grants or technical assistance, tailored to the real capabilities of smaller producers. Future research should focus on monitoring the actual effects of these bonds on the ecological and business performance of companies in our region.

Although green bonds do not represent a universal solution in themselves, they can serve as a significant catalyst for the profound sustainable transformation of the textile industry, provided that there is clear political will, strong institutional support, and active engagement of business entities. The transition from conceptual frameworks and good intentions to concrete measures and systemic changes is a key prerequisite for success. The future of the textile sector largely depends on the ability of policymakers and the business community to align economic interests with the requirements of environmental protection and the principles of the circular economy.

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IMPACT AND BENEFITS OF IMPLEMENTING INFORMATION SYSTEMS IN THE TRANSPORT INDUSTRY

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ABSTRACT: *The global market and new geopolitical conditions, as well as continuous changes in the environment and business methods of companies, require a better understanding of modern business, but also efficient integration and exploitation of data in company business processes, which, on the other hand, imposes the need for permanent generation, development and adaptation of the dynamic architecture of adequate, compatible and efficient management information systems - IS in accordance with the needs of successful business. It is obvious that modern business involves generating innovative, adequate and adaptable IS with large databases, which leads to a situation where certain specific business segments, such as the transport industry (with logistics, supply and warehousing), must have or build their own original and indigenous IS, which should be developed as part of a single automated IS business process with an integrated database. Therefore, the policy of optimal and sustainable business today must insist on reengineering and reducing business costs, with special emphasis on the transport phase, so that logistics (transport, supply, storage) and logistics IS can take on a key role in optimizing business, in terms of savings and business efficiency and achieving competitive advantages. Textile and clothing industry companies carry out transport and logistics in two ways - internally - independently, or according to the principle of third-party logistics - 3PL, with the choice of organizational method mainly depending on the size of the company. The paper presents and analyzes the methods and quality, as well as the effectiveness and efficiency of operations of transport and logistics companies, from the aspect of the necessary segments of the business process - departments of transport and logistics companies (ELD, Dispatch, After hous, Brokers, Dispatch, Maintenance, etc.), but also from the aspect of the implementation of adequate IS (Fleet management, Trello, RingCentral, Keep Truckin, BigRoad, etc.), elements of innovative infrastructure equipment (tachograph, GPS, economizer, etc.), traffic infrastructure data (traffic lights, intersections, toll ramps, speed limits, etc.), as well as terrain configuration data, weather conditions, predictive analytics, etc.*

Keywords: *transport, logistics, IS, optimization.*

UTICAJ I BENEFITI IMPLEMENTACIJE INFORMACIONIH SISTEMA U TRANSPORTNOJ INDUSTRIJI

APSTRAKT: *Globalno tržište i novi geopolitički uslovi, kao i kontinuirane promene okruženja i načina poslovanja preduzeća nalažu bolje razumevanje modernog poslovanja, ali i efikasnu integraciju i eksploataciju podataka u poslovnim procesima preduzeća, što sa druge strane nameće potrebu permanentnog generisanja, razvoja i adaptacije dinamičke arhitekture adekvatnih, kompatibilnih i efikasnih upravljačkih informacionih sistema - is u skladu sa potrebama uspešnog poslovanja. Očigledno je da moderno poslovanje podrazumeva generisanje inovativnih, adekvatnih i adaptibilnih is sa velikim bazama podataka, što dovodi do situacije da pojedini specifični poslovni segmenti, kao što je npr. Transportna industrija (sa logistikom, snabdevanjem i skladištenjem), moraju imati ili graditi svoje originalne i autohtone is, koje treba razvijati kao deo jedinstvenog automatizovanog is poslovnog procesa sa integrisanom bazom podataka. Zato politika optimalnog i održivog poslovanja danas, mora insistirati na reinženjeringu i redukovanju troškova poslovanja, sa posebnim osvrtom na fazu transporta, kako bi logistika (transporta, snabdevanja, skladištenja) i logistički is preuzeli ključnu ulogu u optimizaciji poslovanja, u smislu uštede i efikasnosti poslovanja i ostvarivanju konkurentskih prednosti. Preduzeća tekstilne i odevne industrije, transport i logistiku vrše na dva načina – interno -samostalno, ili po principu logistike treće strane - 3PL, što definišu u svojim strategijama poslovanja, pri čemu izbor načina organizacije uglavnom zavisi od veličine preduzeća. U radu su prikazane i analizirane metode i kvalitet, ali i efektivnost i efikasnost poslovanja preduzeća za transport i logistiku, sa aspekta neophodnih segmenata poslovnog procesa - departmana preduzeća za transport i logistiku (eld, dispatch, after hous, brokers, dispatch, maintenance, itd.), ali i aspekta implementacije adekvatnih informacionih sistema (fleet management, trello , ringcentral, кeep truckin, bigroad, itd.), elemenata inovativne infrastrukturne opreme (tahograf, gps, ekonomonajzer, itd.), podataka saobraćajne infrastrukture (semafori, raskrsnice, naplatne rampe, ograničenja brzine, itd.), kao i podataka konfiguracije terena, vremenskih uslova, prediktivne analitike, itd..*

Ključne reči: *transport, logistika, IS, optimizacija.*

1. INTRODUCTION

Due to the impact of globalization and in conditions of dynamic market competition, new ways of doing business efficiently are necessary today, and thus some elements of business activities, such as transportation, logistics, sales, marketing, public relations, etc., increasingly represent some of the most important elements of successful, efficient and sustainable business. One of the most important links in the process of supply chains for all, including companies in the textile and clothing industry, is the transport of materials

and goods, which, with its adequate technological or organizational solutions, enables the reduction of costs, thereby increasing the productivity and efficiency of business [1, 2]. Transportation today represents one of the most important functions of efficient business, partly due to the high costs it entails, and partly because it is the first (transport of raw materials for production) and last (transport of the finished product to the consumer) element of business processes. On the other hand, new ways of doing business impose the comprehensive inclusion and integration of new technologies and adequate, innovative information systems with a high degree of connectivity and automation, which should enable sustainable competitiveness in all business activities, because the traditional ICT sector is often no longer able to follow the development of new technologies and organizational and business changes [3]. Therefore, effective business optimization measures are necessary, through the permanent generation, adaptation and development of high-quality and efficient business information systems and innovative ways of organizing supply, logistics, transport and storage, which are otherwise based on digitalization and the exploitation of invariant, adaptable and modular information systems, all with the aim of realizing the movement of goods, materials and people in an efficient and optimal manner [4, 5]. With globalization, internationalization of supply chains and global competition, as well as shortening the product life cycle and stricter quality requirements, logistics and transport processes have become significantly more complex and dynamic today, and thanks to advanced technologies, modern transport logistics is rapidly changing and achieving more efficient, faster and more sustainable distribution of goods and resources. Today, transport represents one of the most important logistics functions, and due to the complexity of the transport logistics process, external transport operations, as well as warehousing, packaging, consulting, etc., are increasingly implemented according to the principle of third-party logistics - 3PL, i.e. they are assigned to specialized companies for the transport of goods and materials - logistics transport providers. The introduction of modern technologies, such as automated warehouses, real-time supply and tracking systems, or transport management systems - TMS, further increases efficiency and business optimization opportunities [6].

2. TRANSPORT INFORMATION SYSTEMS

The paper presents information systems that should be part of a transport and logistics company (Trello, RingCentral, Fleet management, Keep Truckin, BigRoad, etc.), viewed first from the aspect of the functions and importance of the information systems themselves in the business of transport and logistics companies, then from the aspect of necessary and possible segments of the business process - departments of a transport and logistics company (Maintenance, ELD, Brokers, Dispatch, After hous, etc.), as well as from the aspect of innovative infrastructure equipment (tachograph, GPS, economizer, etc.), traffic infrastructure data (traffic lights, intersections, toll plazas, speed limits, etc.) and terrain configuration data, weather conditions, predictive analytics, etc.. It is obvious that every proposal for the implementation of such information systems depends on many influencing factors - the size of the company, the quantitative and qualitative structure of employees,

the quantitative and qualitative structure of vehicles, the technical and technological equipment of the company, the business strategy, the type, scope and method of work and business, the compatibility and adaptability of information systems, the possibility of integrating different sectors and achieving greater coordination and speed of implementation of business activities, etc.. It should be noted that the number and types of departments, as well as the number and types of information systems, may vary in practice and are part of the business strategy of the company, because each specific company must shape its transport and logistics systems and its departments, according to its requirements and to the extent that they are needed to realize its own goals, as opposed to the divergent goals of other participants [3].

- The **MAINTENANCE** department does not only involve vehicle maintenance, but as technical support it represents one of the key connections between drivers and truck owners. Vehicle - truck maintenance (tire condition, towing, complex mechanical breakdowns) does not end with regular services, but requires a team of experts who continuously monitor the technical condition of each vehicle at all times, providing quick and efficient repairs, in order to ensure safety and assistance on the road. Such an approach requires a quality connection with the fleet and drivers, but also a network of workshops throughout the business area – the country where the business is conducted, in order to be able to intervene quickly and efficiently and provide adequate assistance at preferential prices.

  The most famous programs – application software used in vehicle maintenance tasks are:

  ○ **Trello** – a visual platform for managing tasks and projects in the field of maintenance, with elements such as: Table - PM Board – a place for overall task organization, progress tracking and distribution of tasks and responsibilities, List – with separate offers - columns (e.g. PM-DOT active, to be worked on, to do, in progress, done, etc.) and Card – individual tasks and ideas (e.g. create a logo, write text, test the application, etc.). Task descriptions can be added to the above lists, deadlines can be set, attachments (files, images, links, etc.), comments can be written, checklists can be created, etc.

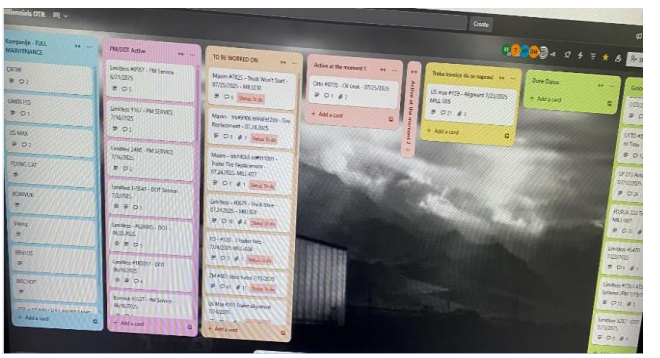

Figure 1: Trello, a visual task and project management platform

- **RingCentral** is a cloud-based communications platform that offers a comprehensive set of tools for phone calls, messaging, video conferencing, etc., and is used in business environments to help teams, drivers, and businesses communicate, manage tasks, and connect with customers. RingCentral does not have high technology as its key tools, but VoIP telephony (telephony over the Internet), video calls and conferences (so that teams can work together, even though they are not physically in the same place), as well as messaging - chat (allows fast internal communication between team members), shows the importance of digitalization and the implementation and exploitation of Internet technologies.

➢ As a key role in transport and logistics is played by brokers, whose main job is to connect carriers (truckers, freight forwarders) with companies that want to transport goods, it can be said that the **BROKERS** department includes the work of connecting clients and carriers, as well as acting as an intermediary between companies that send goods and carriers (truck, ship, plane), negotiating transport conditions and prices, thus the importance of the existence of this department is imposed. The most famous application software - programs that brokers can use to make transport companies operate more efficiently include:

- **Highway** application – which is a specific platform that offers vehicle tracking capabilities, route optimization, as well as logistics services for carriers - truck drivers and transport companies, focuses on optimizing daily operations in the transport industry, helping to reduce costs and increase efficiency. It can be said that the Highway application connects carriers and drivers with companies, that is, it serves as an intermediary between carriers and companies that have cargo to transport, then optimizes the route, and also tracks vehicles and deliveries, while through the Fleet management function, it automates and manages the fleet, as it enables monitoring of driver working hours, vehicle condition, fuel consumption and other parameters that are key to optimizing operations.

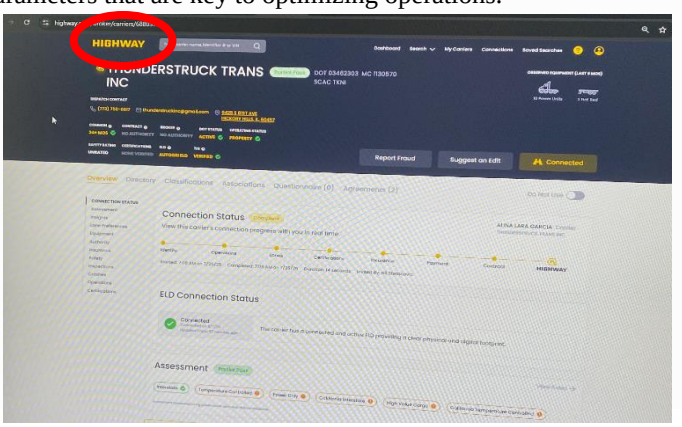

Figure 2: Highway app home page

- **Carrier411** - the online platform is another application of the Brokers department, which is used to check the credibility and rating of carriers, but also to check certificates, licenses, etc. In fact, the purpose of the Carrier411 program is to connect companies that send goods - shippers and brokers with carriers (drivers and transport companies), so that all participants can participate and make the best decisions for their own business. As the main task - the Carrier411 function, we can highlight checking the credibility and history of carriers (including information on accident history, delivery delays, complaints or other negative aspects of the business, which helps businesses make the best decisions about choosing a carrier), and then tracking and rating , as well as displaying the status of the carrier (quickly identify reliable carriers, as well as data on the carrier's insurance coverage, licenses and registrations). In addition to the above, some of the tasks of this application include searching for carriers according to various criteria (such as vehicle type, geographic location, type of services, or specific transportation needs), as well as creating reports and analyses, tracking complaints and problems, as well as assisting companies in verifying carrier certificates and insurance.

- In the transport industry, safety is of course the priority, as the risks on the road can be significant, so it is important to have a professional team that deals exclusively with safety issues, i.e. a safety team that ensures drivers, transport and logistics companies act in accordance with legislation, safety standards and best practices in the transport industry. In the transport industry, that specialized team responsible for safety at all levels of transport operations and with a key role in reducing risks, preventing accidents and guaranteeing the legality and safety of the transport of goods and people, is the **SAFETY** department.

  Therefore, monitoring safety standards and regulations (including local, national and international laws, as well as industry guidelines - e.g. FMCSA in the US, EU regulations, etc., as well as vehicle control by ensuring regular inspection and compliance with technical and safety standards), managing safety training (with safety procedures, traffic rules, use of safety devices and behavior in emergency situations, as well as accident prevention training), and accident prevention with the inclusion of traffic accident analysis and monitoring of driver behavior (speed, phone use, braking speeds, etc.), are key responsibilities of the Safety Team. Modern and innovative tools and technologies used by the Safety Team are most often vehicle tracking systems (GPS, telemetry), in-vehicle surveillance cameras (for monitoring driver behavior and road conditions), safety sensors (braking, speed, temperature, fuel levels), software for analyzing data on accidents, traffic conditions, and driver behavior, as well as training applications, and one such program used by the Safety Department is ProTransport:

- **ProTransport** as a software program represents a specialized platform for managing transport and logistics operations, designed to help carriers, brokers, logistics companies and other actors in the transport industry to optimize their operations, increase efficiency and reduce costs. The application contains a drop-

down menu with various tool groups (Dispatch, Safety, Accounting, etc.) and their tool offerings (Truck, Maintenance, etc.), related to the transportation industry

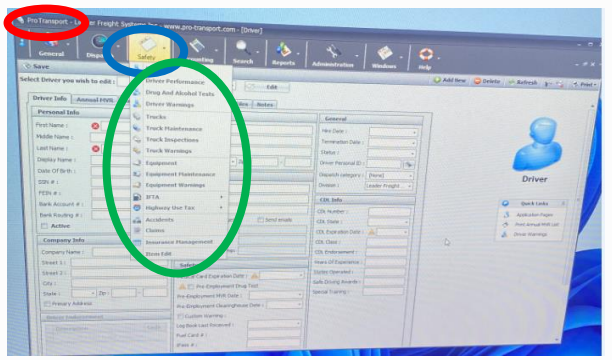

Figure 3: ProTransport software program

Order and transport management, viewed through the receipt and tracking of orders (including cargo type, date and time of transport, destination and other relevant data), as well as through transport allocation and planning and automatic assignment of transport in the safest and most efficient manner, can be highlighted as one of the main tasks of the ProTransport software.

- **ELECTRONIC LOGGIN DEVICE** – ELD is an application used to automatically track driver hours in the transportation industry, and is the name of one of the departments of transportation and logistics companies. ELD devices and applications replace traditional manual logs, allowing drivers and carriers to accurately track the number of hours they spend behind the wheel in order to comply with driver time legislation. In addition to tracking working hours as the main function of an ELD application, this application also deals with compliance with laws (e.g. FMCSA in the US) and connecting to the vehicle, usually via OBD - On-Board Diagnostics devices or other technological interfaces, to automatically track data on speed, distance traveled and vehicle status, managing reports that can be easily shared with superiors, inspectors or regulatory bodies, and also allows for tracking rest periods. The most well-known ELD applications used today include Keep Truckin, Samsara, BigRoad, ELD Mandate, Geotab, and others.
- As dispatchers play one of the key roles in transport and logistics and many other industries, where it is necessary to coordinate workflows and manage resources in the field, the **DISPATCH** department is also necessary and has one of the most important roles in the business process of transport and logistics companies. One of the functions of the dispatcher is to communicate with drivers, providing information about new assignments, as well as route updates or necessary changes, and may also be responsible for resolving problems during the ride, such as vehicle breakdowns or accidents. It should be noted that in addition to the by default technical literacy, dispatchers must also have special abilities, such as a sense of organization and planning, communication skills, as well as the so-called problem-

solving skills, in order to organize the work of the Dispatch department in a quality and efficient manner. Of course, in this work, dispatchers very often use various application software and other technical and technological capabilities, such as Fleet management software, GPS tracking, ELD applications, etc., to ensure that the work of the dispatcher is timely and efficient.

- **AFTER HOURS TRACK AND TRACE** department is dedicated to providing continuous support to drivers and customers - 24 hours a day, seven days a week, and represents the first line of support. In transportation, After hours brings many advantages in terms of flexibility, efficiency and service improvement, and although it carries certain challenges, with proper management it can allow carriers to provide better customer service, reduce delivery times and respond to urgent requests, which for businesses and industries where time is of the essence, shows that After hours operations can be crucial for competitiveness and profitability. It is interesting that, apart from the usual innovative internet communication and tracking systems (sensors, GPS, etc.), this department does not have its own special IS, which indicates the importance of digitalization and the internet for efficient business.
- In times of quantitative and qualitative shortages of human resources - labor, the **RECRUITMENT** department gives a special stamp to the quality and prospects of transport and logistics companies. The Recruitment application can be treated as a specific labor market (truck drivers), which is also the specificity of the Recruitment department, which deals with the recruitment of truck drivers, but also with connecting companies that need drivers and the drivers themselves, which involves daily contact with drivers and providing information about job opportunities and working conditions, but also contact with clients looking for drivers, in order to make the recruitment process, as well as the percentage of success in connecting drivers and companies, as efficient as possible.

In addition to the above, there are other business process departments with their own information systems, which could also, or should, be an integral part of the integral information systems of a transport and logistics company, which of course depends on many business parameters, such as: the size of the company, the type of production or service, the technological and technical equipment of the company, the quantitative and qualitative structure of human resources - employees, the wishes and possibilities of initial investments, the technical and road infrastructure of the area in which it operates, etc. For example, it is obvious that the **SALES**, **MARKETING** or **ACCOUNTING** departments are universal departments of many companies and business processes, so their implementation is subject to special consideration and review according to many parameters [6].

3. ANALYSIS AND DISCUSSION

Through research and continuous analysis of the work and development of transport companies, with a special focus on the implementation of information systems and business automation, the problem of segmentation - partial digitalization and automation, or partial

implementation of information systems, has been identified, which reduces business efficiency and sustainable competitiveness in the open global market [4, 7].

Since the paper deals with the impact and benefits of implementing transport information systems, as well as the analysis of innovative technical and technological solutions for transport and road infrastructure and the possibilities and needs of generating departments of transport companies, i.e. the efficiency of transport company operations depending on qualitative changes in terms of implementing innovative technologies and adequate information systems, but also by generating specific departments of the business process, some regularities can be observed and listed that need to be examined in more detail (by experiment, case study, etc.) and set as rules that should be followed when generating strategies for companies in the transport industry:

- For the efficient and successful operation of transport companies, adequate (according to certain parameters - type of business, number of employees, etc.), indigenous (personal for each company), and compatible (mutually coordinated and supported) information systems are necessary.
- The positive effects of implementing adequate information systems and innovative infrastructure equipment - Personal Digital Assistant devices - can be observed in all phases of the business process, and therefore they are recommended as a mandatory component of adequate departments and business processes of transport companies.
- The generation and implementation of information systems depend on many influencing factors: the size of the company, the quantitative and qualitative structure of employees, the quantitative and qualitative structure of vehicles, the technical and technological equipment of the company, the business strategy, the type, scope and method of work and business, the compatibility and adaptability of information systems, the possibility of integrating different sectors and achieving greater coordination and speed of implementation of business activities, etc.
- Information systems should be generated in a way that directly or indirectly affects savings in terms of time, material and human resources, be mutually compatible and easily and quickly integrated into business processes in accordance with the type of work and the relevant departments.
- The modern market requires specialized and modern transport companies to constantly monitor trends, as well as improve and upgrade their methods of work and business, which largely involve elements of digitalization, information systems and the Internet, and innovative technologies, i.e. elements that enable an easier, more precise and more cost-effective process of organizing and planning transport logistics [5].
- Since the overlap of a large number of information system functions is obvious, it is necessary to analyze the tasks of the department in more detail, and then align the information systems with the needs. In fact, before developing an application, it is necessary to collect a large amount of data on the needs and requirements of the department and the business process, but deeper coordination and cooperation with direct executors in the department (engineers, managers, etc.) is also necessary.

- For successful and efficient business today, it is necessary to generate a uniform and integrated database, on whose basis – data, the work of the company itself would be based, as well as the work of all integrated information systems of a business process [7].
- Partial information systems partially improve the business operations of a company, but efficient operations and successful optimization of the business process are possible only by generating a total - integrated business process information system, composed of individual and compatible information systems, but with a common - unified database [6, 8].
- The company's work and business strategy must be aligned with innovative solutions, implemented information systems, and generated specific departments, where it should be emphasized that the number and types of departments, as well as the number and types of information systems, may vary in practice and are part of the company's business strategy, because each specific company must design its transport information systems and its departments, according to its requirements and to the extent that they are needed to realize its own goals, as opposed to the divergent goals of other participants [6].
- The Maintenance Department, with its timely and adequate actions, modern tools and adequate information systems (Trello, Ring Central, etc.), precise diagnostics, as well as a network of workshops and parts stores with which it has cooperation agreements, can guarantee minimal downtime, and thus reduce maintenance costs by 20% to 50%, and therefore should be an indispensable component of the business process.
- It should be noted that in addition to the Maintenance department, the Safety department with the ProTransport platform and safety sensors (braking, speed, temperature, fuel level), as well as Recruitment, which deals with the selection of drivers, whose skills and training can significantly influence fuel consumption (driving style, acceleration, braking, etc.), are closely linked in terms of savings for the material - fuel consumption parameter [9].
- The Brokers department also deserves its place in the business process, because by exploiting adequate, specific and original application software (Highway, Carrier411, etc.), they can optimize costs, increase efficiency, reduce administrative burden, or access a larger network of carriers and number of clients faster and more efficiently.
- Monitoring safety standards and regulations (local, national and international laws, as well as industry guidelines - e.g. FMCSA in the USA, EU regulations, etc.), as well as vehicle control by ensuring regular inspections and meeting technical and safety standards, are the foundation of the Safety Department, which as such is an indispensable part of efficient operations.
- Efficient order and transport management, seen through the receipt and tracking of orders and including the type of cargo, date and time of transport, destination and other relevant data, as well as through transport allocation and planning and automatic assignment of transport in the safest and most efficient manner, are the

tasks of the ProTransport software, which this software (of the Safety Department) recommends as mandatory.

- A modern monitoring system and automatic registration, management and control of driver working hours spent on the road, on standby or during rest periods, actively working on fatigue prevention and increasing safety, with a tendency to comply with HOS regulations and legislation, are some of the functions of the Electronic Loggin Device - ELD department and application, which directly recommend this information system and department as mandatory in transport companies.
- The Dispatch department is responsible for planning daily tasks, organizing and monitoring vehicle movements (including destinations, routes and delivery or transportation times), creating schedules and allocating resources, as well as communicating with drivers and optimizing routes through various technologies (Fleet management, GPS, radio, mobile applications, etc.), which ensures timely execution of tasks and time savings on the one hand and seriously recommends this department to the group of mandatory departments, on the other hand, with a free choice of the type and number of applications.
- One of the very current specific departments today, which is increasingly sought after and recommended in all types of businesses and all industries, is the After hous department, or in the transport industry known as After hours track and trace, otherwise dedicated to providing continuous support to drivers and clients, where speed and delivery time are crucial (emergencies, international transport, perishable goods, etc.), co as such, it clearly has a direct impact on saving time and efficient business (with an indirect connection to the Brokers and Sale departments, but also to most other departments).

Ultimately, it can be said that digitalization, transport information systems and innovative infrastructure equipment enable more precise tracking of goods and materials in real time, as well as inventory optimization and reduction of operating costs, thus increasing the competitiveness of companies in the global market. All of this, as well as warehouse automation, the increasing presence and exploitation of artificial intelligence elements in route planning, predictive analytics and IoT technologies [10], represent new key elements that will transform existing business methods in the coming period, improve speed and accuracy, reduce overall costs and enable quantitative and qualitative business growth.

6. CONCLUSION

New technologies (digitalization, information systems, internet of things, cloud, etc.) are creating completely new business environments, and therefore a different business architecture, with the possibility of rapid and adequate changes in business processes and the impact on the generation and development of new and efficient business models, which is the basis for the impact and possibility of further development of all industries, including the transport industry. Specific business information systems of the transport industry enable easier and more precise integration of different sectors of the business process, achieve greater coordination and speed of business activities, create opportunities for

monitoring and managing the fleet and the transport of goods and materials, analyze business trends, optimize routes and generally optimize the business process, with the implemented infrastructure equipment and specific and indigenous information systems becoming key tools in making strategic decisions and maintaining a company's competitive advantage. On the one hand, it can be concluded that the generation and implementation of information systems depend on many influencing factors: the size of the company, the quantitative and qualitative structure of employees, the quantitative and qualitative structure of vehicles, the technical and technological equipment of the company, the business strategy, the type, scope and method of work and business, the compatibility and adaptability of systems and departments, the possibility of integrating different sectors, achieving greater coordination and speed of implementation of business activities, etc., while on the other hand, it can be concluded that information systems should be generated in such a way that they directly or indirectly affect savings in the most important parameters of the business process - time, material and human resources, to be adaptable and mutually compatible and to be easily and quickly integrated into business processes, in accordance with the type of work and adequate departments.

Specific separate information systems of the transportation industry, such as Fleet management, Trello, RingCentral, Keep Truckin, BigRoad, ELD Mandate, Samsara, Geotab, Cape, TransAudit, etc., enable easy, precise and efficient integration of different sectors of the business process - Maintenance, Dispatch, Brokers, Safety, Recruitment, etc., create opportunities for easier monitoring and management of the fleet and the transport of goods and materials, and achieve greater coordination and speed of business activities.

It should be noted that modern business today involves the generation of innovative, adequate and adaptable information systems, but with large integrated databases, which leads to a situation where some specific business processes, such as the transport industry (with logistics, supply and warehousing), must have or must generate their own original and indigenous information systems, which should be developed as part of a single integrated business process information system, with an integrated database.

Since segmental digitalization and implementation of information systems only partially improve company performance, it is recommended to generate innovative and original integral information systems with a single database, which will, under a single interface and through various applications, unify data from all business process information systems, infrastructure equipment and traffic infrastructure data, terrain configuration and weather conditions, thus enabling management to make a high-quality selection of the best business solutions, and the company to effectively optimize its operations and strengthen its competitiveness.

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USE OF LEAN MANAGEMENT IN AUTOMOTIVE TEXTILE INDUSTRY IN SHTIP, NORTH MACEDONIA – ORGANIC OR MECHANIC APPROACH

Scientific paper
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ABSTRACT: *This study examines the application of Lean management in the automotive-textile industry, exploring whether companies perceive Lean as a technical tool for achieving rapid operational efficiency or as a comprehensive management philosophy that evolves through people and organizational culture. In practice, many Lean implementations remain limited to processes and technical tools, while neglecting philosophy, people, and systematic problem-solving, resulting in short-term improvements that fail to sustain continuous improvement over time. This challenge is particularly significant in labor-intensive manufacturing processes, such as sewing, where investment in human capital and the development of a strong organizational culture are essential for achieving long-term efficiency and organizational stability. The findings highlight the importance of adopting a balanced approach to all elements of Lean management in order to support sustainable development and enhance organizational competitiveness.*

Keywords: *Lean management; Toyota Production System (TPS); organic and mechanical approach; automotive-textile industry; organizational culture.*

PRIMENA LEAN MENADŽMENTA U AUTOMOBILSKO-TEKSTILNOJ INDUSTRIJI U ŠTIPU, SEVERNA MAKEDONIJA – ORGANSKI ILI MEHANIČKI PRISTUP

APSTRAKT: *Istraživanje analizira primenu Lean menadžmenta u automobilsko–tekstilnoj industriji, pri čemu se razmatra da li kompanije Lean shvataju kao tehnički alat za brzu efikasnost ili kao živi sistem koji se razvija kroz ljude i organizacionu kulturu. Praksa pokazuje da mnoge implementacije ostaju ograničene na procese i alate, uz zanemarivanje*

filozofije, ljudi i rešavanja problema, što dovodi do kratkoročnih rezultata i neodrživosti kontinuiranog unapređenja. Posebno u radno intenzivnim manuelnim procesima kao što je šivenje, ulaganje u ljude i izgradnja organizacione kulture predstavlja ključni faktor za dugoročnu efikasnost i stabilnost. Analiza naglašava potrebu za uravnoteženim pristupom svim elementima Lean-a, kako bi se obezbedio održivi razvoj i konkurentnost.

Ključne reči: *TPS, Lean menadžment, Organski i mehanički pristup, Automobilska industrija, Tekstilna industrija.*

1. INTRODUCTION

In today's rapidly evolving business environment, Lean management has become one of the most influential management philosophies worldwide. Its primary objective—the elimination of waste and the resulting improvement in operational efficiency and cost reduction—has encouraged many organizations to adopt Lean principles. However, the long-term sustainability of Lean implementation remains a significant challenge, particularly when Lean is applied as a collection of technical tools rather than as a comprehensive management philosophy.

The **Toyota Production System (TPS)** is widely recognized as the foundation of Lean production and has profoundly influenced modern manufacturing and management practices over the past three decades. Built on the principles of continuous improvement (*Kaizen*) and respect for people, Lean management extends far beyond the application of technical methods and process optimization. Instead, it represents a holistic management philosophy that integrates organizational culture, employee development, and systematic problem-solving. Nevertheless, many organizations continue to implement Lean primarily as a cost-reduction initiative, focusing on operational tools while overlooking the cultural and human dimensions that are essential for sustainable success.

Such a mechanistic approach may generate short-term improvements; however, it often fails to produce lasting organizational transformation and may ultimately compromise the sustainability of Lean initiatives. The true essence of Lean lies in its role as a continuous learning system that promotes teamwork, employee engagement, disciplined processes, and continuous organizational improvement. Consequently, Lean should not be regarded as a collection of tools for achieving rapid results, but as a long-term management philosophy that requires sustained investment in people and the development of a strong organizational culture.

As Liker emphasizes [1] , *"Toyota calls its operators 'team members,' and managers speak of them with deep respect because these are the people who directly contribute to making the product and are dedicated to continuous improvement."* This perspective highlights one of the fundamental principles of Lean management: sustainable organizational success depends not only on efficient processes but also on the continuous development, engagement, and empowerment of people.

Therefore, the objective of this study is to examine how Lean management is perceived within an automotive-textile company in Štip, North Macedonia, and to determine whether managers primarily adopt an organic perspective, which emphasizes people and organizational culture, or a mechanical perspective focused on technical tools and process efficiency.

2. MATERIALS AND METHODS

The study was conducted in a modern company operating within the automotive-textile industry, which is part of a global corporation headquartered in North Macedonia. The company has been operating for more than ten years and employs over 1,000 people. As part of its continuous improvement strategy, the company has implemented various contemporary management practices, with Lean management representing one of its principal organizational challenges.

The study population consisted of 35 respondents from different levels of the organizational hierarchy. The first group included the General Manager and operational sector managers, while the second group comprised coordinators who, although positioned one level below management, are responsible for supervising a substantial number of employees. Data were collected using a structured questionnaire based on a five-point Likert scale to assess managerial perceptions of Lean management. The questionnaire was designed to determine whether respondents perceive Lean primarily as a comprehensive management philosophy (organic approach) or as a technical system focused on waste elimination and operational efficiency (mechanical approach).

The conceptual framework of the study is based on the 14 principles of Lean management and Liker's 4P model, consisting of Philosophy (long-term vision and values), Process (efficient and standardized workflows), People (employee development, motivation, and organizational culture), and Problem Solving (continuous learning and systematic improvement). These four dimensions provided the analytical framework for evaluating managerial perceptions of Lean implementation [1].

3. RESULTS AND DISCUSSION

Figure 1 presents the distribution of respondents' perceptions across five categories: **organic approach, mechanical approach, between organic and mechanical, traditional approach,** and **don't know/no opinion**. The analysis was conducted according to the four pillars of Lean management defined by the 4P model: Philosophy, Process, People, and Problem Solving.

Philosophy - The **mechanical approach** represents the dominant perception (46%), indicating that Lean is primarily viewed as a technical method for eliminating waste rather than as a comprehensive management philosophy. Since philosophy constitutes the foundation of the Lean 4P model, this finding is particularly significant. A predominantly mechanical understanding of Lean influences not only process design but also organizational culture, employee development, and approaches to continuous

improvement. **This finding suggests that the organization places greater emphasis on operational efficiency than on developing a long-term Lean culture. Consequently, the sustainability of Lean initiatives may be limited if organizational values and leadership commitment are not strengthened. This observation is consistent with previous studies, which indicate that many organizations initially adopt Lean as a set of technical tools for improving operational efficiency while giving insufficient attention to organizational culture and leadership, thereby limiting the long-term sustainability of Lean transformation** [2,3].

Process - No clearly dominant approach was identified within the **Process** dimension. Although the mechanical approach accounts for the largest proportion of responses (30%), the remaining categories show relatively similar distributions. This suggests that the company has successfully adopted many Lean tools and standardized processes; however, these practices do not appear to be fully supported by a shared organizational philosophy capable of ensuring long-term sustainability. **The relatively balanced distribution of responses indicates that process improvements have been implemented, but they are not yet fully integrated into a coherent Lean management system.** Previous research suggests that implementing Lean tools without embedding them within a broader organizational philosophy often leads to fragmented improvements rather than a fully integrated Lean production system [3].

Pepole - Within the **People** dimension, the **organic approach** received the highest proportion of responses (33%), indicating a positive orientation toward employee development and investment in human capital. **This finding supports studies emphasizing that employee engagement, leadership, and organizational culture are fundamental enablers of successful Lean implementation** [2,4]. Nevertheless, the relatively balanced distribution across the remaining categories suggests that the strategic importance of employees as drivers of continuous improvement has not yet been consistently recognized throughout the organization. **Considering that the automotive-textile industry is highly labor-intensive, strengthening employee involvement, continuous training, and empowerment is essential for achieving sustainable Lean implementation.**

Problem Solving - The responses within the Problem Solving dimension reveal no dominant approach. The highest proportion of responses falls within the category between organic and mechanical (30%), while the mechanical (29%) and organic (28%) approaches are almost equally represented. This distribution indicates that problem-solving practices remain insufficiently integrated into a coherent Lean philosophy and highlights the need for a more systematic organizational approach to learning and continuous improvement. The absence of a dominant approach may reflect an incomplete Lean transformation, as previous studies have identified inconsistent problem-solving practices and insufficient organizational learning as common barriers to sustainable Lean implementation [5]. The absence of a clearly dominant approach may indicate that structured problem-solving methods are applied inconsistently across different organizational levels, reducing the organization's ability to achieve continuous improvement through organizational learning.

Overall, the results indicate that Lean management within the studied company is still predominantly perceived through a mechanical perspective, particularly in the dimensions of Philosophy and Process. Although the People dimension demonstrates a greater orientation toward the organic approach, the findings suggest that a stronger integration of Lean philosophy, organizational culture, and employee development is necessary to achieve sustainable continuous improvement and long-term organizational competitiveness.

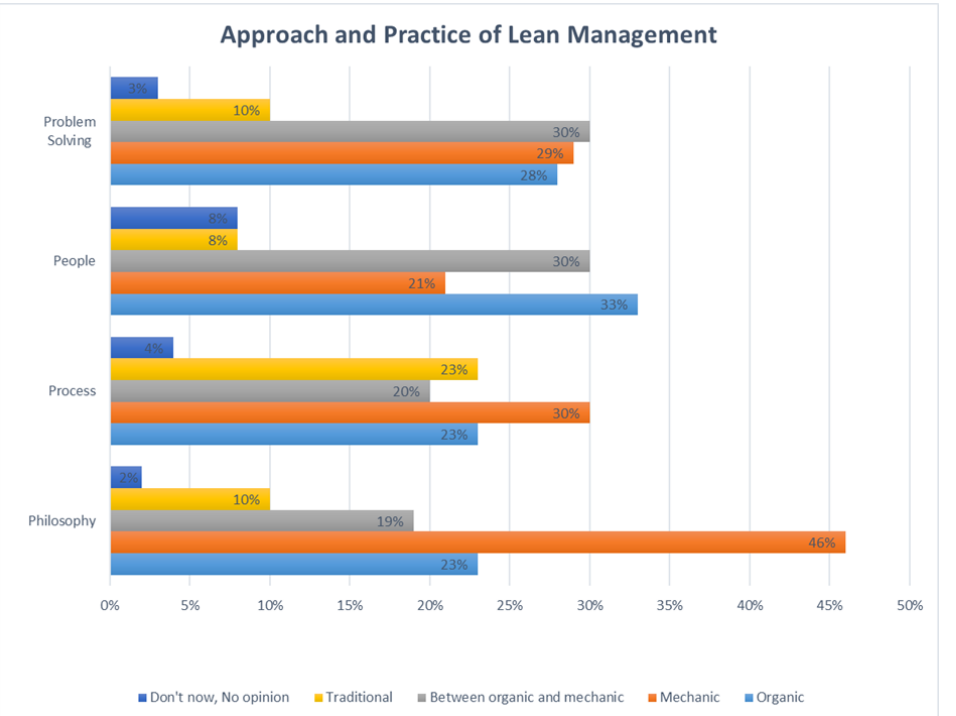

Figure 1: Distribution of managerial perceptions of Lean management according to the four dimensions of the 4P model

4. CONCLUSION

The findings indicate that the studied company demonstrates a predominantly mechanical orientation in the dimensions of Philosophy and Process, while the People dimension reflects a moderate organic orientation. In contrast, the Problem Solving dimension shows no clearly dominant approach, suggesting that Lean practices have not yet been fully integrated into a coherent management philosophy. Overall, the results indicate that Lean management is still perceived primarily as a technical system for improving operational

efficiency and reducing costs rather than as a comprehensive management philosophy that promotes continuous learning, employee development, and organizational culture.

These findings are particularly significant because the company operates within the labor-intensive automotive-textile industry, where organizational performance depends largely on employees' knowledge, skills, motivation, and engagement. In such an environment, sustainable competitiveness cannot be achieved solely through process optimization and the implementation of Lean tools. Instead, long-term success requires the integration of Lean philosophy with organizational culture, leadership commitment, and continuous employee development.

The study confirms that strengthening the organic dimension of Lean management is essential for achieving sustainable organizational improvement. Developing a culture of continuous learning, teamwork, employee empowerment, and systematic problem-solving should become strategic priorities for organizations seeking to maximize the benefits of Lean implementation. As Liker emphasizes [1], *"Continuous improvement and respect for people are inseparable. Without people who are engaged and developed, continuous improvement cannot be sustained."* This principle reinforces the central finding of the present study that people represent the most important driver of successful and sustainable Lean transformation.

This research contributes to the understanding of Lean implementation within the automotive-textile industry by demonstrating that the balance between the technical and human dimensions of Lean remains a significant challenge in practice. The findings provide managers with practical guidance for designing Lean strategies that extend beyond process optimization and incorporate organizational culture, employee development, and long-term strategic thinking.

The study is limited to a single company, and therefore the findings cannot be generalized to the entire automotive-textile industry. Future research should include comparative studies involving multiple companies and different manufacturing sectors, as well as examine the relationship between Lean maturity, organizational culture, leadership, and business performance.

In conclusion, organizations seeking sustainable Lean transformation should move beyond a predominantly mechanical implementation of Lean and embrace its broader philosophy as a people-centered management system. Only through a balanced integration of Philosophy, Process, People, and Problem Solving can organizations achieve continuous improvement, long-term competitiveness, and sustainable organizational development.

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REVIEW OF EXISTING TEXTILE-COVERED SPORTS FACILITIES IN NIŠ, SERBIA

Review paper
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ABSTRACT: Textile architecture in Serbia is predominantly present in its simpler forms. In most existing buildings, textile membranes are used only as a covering material, without the significant double curvature required to fully exploit their structural and architectural potential. This research focuses on sports facilities covered with textile membranes in the city of Niš. The aim of the study is to identify and systematize existing buildings of this typology. The results show that there are currently 20 such facilities in the wider area of the city. These facilities were visited, and relevant data were recorded and analyzed, with the results presented and discussed in this paper. In addition, six other textile-covered structures were identified but fall outside the scope of this research. These include four storage facilities, one protective cover for a historical site, and one canopy covering a restaurant garden. The analyzed textile structures exhibit significant diversity in several aspects, including ownership, structural system, permanence, and function. The findings of this study will be used to inform the development of improved textile cover designs for sports facilities in the region.

Keywords: *Textile architecture, textile membranes, sports facilities, textile buildings.*

PREGLED POSTOJEĆIH SPORTSKIH OBJEKATA POKRIVENIH TEKSTILNIM MEMBRANAMA U NIŠU, SRBIJA

APSTRAKT: *Tekstilna arhitektura u Srbiji pretežno je prisutna u svojim jednostavnijim oblicima. U većini postojećih objekata, tekstilne membrane se koriste samo kao pokrivni materijal, bez značajne dvostruke zakrivljenosti koja je potrebna da bi se u potpunosti iskoristio njihov konstruktivni i arhitektonski potencijal. Ovo istraživanje se fokusira na sportske objekte pokrivene tekstilnim membranama u gradu Nišu. Cilj rada je identifikacija i sistematizacija postojećih objekata ove tipologije. Rezultati pokazuju da se trenutno na širem području grada nalazi 20 takvih objekata. Ovi objekti su posećeni, a relevantni podaci su prikupljeni i analizirani, pri čemu su rezultati prikazani i razmatrani u ovom radu. Pored toga, identifikovano je još šest objekata pokrivenih tekstilom, ali oni ne*

spadaju u obuhvat ovog istraživanja. To uključuje četiri skladišta, jednu zaštitnu konstrukciju za istorijski lokalitet i jednu nadstrešnicu koja pokriva baštu restorana. Analizirane tekstilne konstrukcije pokazuju značajnu različitost u mnogim aspektima, u pogledu vlasništva, primenjenog konstruktivnog sistema, stalnosti i funkcije. Rezultati ovog istraživanja biće korišćeni kao osnova za razvoj unapređenih rešenja tekstilnih pokrivača za sportske objekte u regionu.

Ključne reči: *Tekstilna arhitektura, tekstilne membrane, sportski objekti, tekstilni objekti.*

1. INTRODUCTION

Textile architecture has become increasingly popular over the past 50 years. In many countries, it is widely used across different building typologies. The reasons for using textile materials on roofs or façades are sometimes aesthetic, due to their attractive curvature, and sometimes practical, owing to the numerous benefits they offer. Compared to traditional building materials, architectural textiles are not only visually appealing but also extremely lightweight, possess high tensile strength, are easy to transport, relatively inexpensive, and durable. On the other hand, the technological processes involved in their development are complex and still not fully optimized, particularly in terms of the reliability of mechanical properties.

It is generally considered that the full potential of textile architecture is not yet utilized in Serbia and that such buildings are less common than in more developed countries. The conducted research confirms that textile buildings are indeed less numerous, despite the presence of experts in this field. However, the investigation also revealed a disproportion in the distribution of textile buildings by typology. The majority are sports facilities, followed by industrial storage structures, while other types are rare. This research therefore focuses on textile-covered sports facilities.

Previous studies have investigated various aspects of textile membrane roofs. The most common topics include thermal comfort [1–3] and energy performance [4,5]. A specific subtype includes air-supported textile membrane structures [6,7]. The most frequently analyzed typologies are industrial [8] and sports facilities [9–11]. Identification studies of textile-covered sports facilities have been conducted in the region [12], while examples from Italy are presented in [13]. Advanced textile structures in Serbia have also been analyzed [14].

This research reviews existing sports facilities covered by textile membranes in the wider area of the city of Niš. The goal is to identify and document all such buildings to establish a foundation for further detailed analysis. The resulting database will be used to assess their architectural and structural characteristics and to support the development of optimized design solutions. It is expected that the findings will contribute to promoting textile architecture in the region.

2. METHODOLOGY

The geographical scope of the research is limited to the wider area of the city of Niš, the third-largest city in Serbia. The city has approximately 180,000 inhabitants, while the wider area includes around 250,000. The climate is moderate continental, with an average annual temperature of 11.9°C, approximately one rainy day in three, and an elevation of about 200 m. Niš is located in the southeastern part of the country, along an important transit route between Europe and the Middle East. It was selected as the initial case study, with the intention of extending similar research to other major cities.

The study focuses exclusively on sports facilities, although other textile-covered structures exist in the city. This focus was chosen because sports facilities represent the dominant typology and therefore provide the most comprehensive dataset. Only medium- to large-span structures were considered, excluding textile roofs with spans smaller than 10 m. The analysis was conducted between January and April 2026.

The research began with the identification of textile-covered buildings in Niš. Initial data were collected through informal interviews with athletes, followed by internet searches and map-based analysis. After compiling a preliminary list, each identified building was visited in person. Data on architectural and structural characteristics were recorded during these visits.

Due to the lack of access to official design documentation, certain data, such as the exact type of textile material, could not be obtained. Consequently, the research focused on observable and accessible characteristics. This paper presents the locations and exterior views of the identified buildings, while other relevant aspects are analyzed and discussed. The conclusions drawn from this phase will inform subsequent stages of the research.

3. RESULTS AND DISCUSSION

The conducted analysis identified 26 textile buildings in the wider area of Niš. Among these, there were six buildings that fall outside the scope of the research. These include one large-span structure used as a protective cover of the historical site Medijana, which contains a Roman complex in the eastern part of the city, and one double-cone cover of a restaurant garden in the northern part of the city. Additionally, there are four industrial textile buildings: a small one in the north, two that are part of a milk factory in the far northwest, and one storage facility of a retail store in the west. They are marked with orange tags in Figure 1. The remaining 20 are all sports facilities. Their locations on the city map are shown in Figure 1 as blue circles.

In Figure 1, these buildings are numbered starting from the east; however, building number 20 is intentionally labeled last. The reason for this is that the building existed when the research began; nevertheless, the textile cover was dismantled before the physical visit to the facility. Therefore, it is known that this textile roof existed, and some data about it are available from the owner and historical imagery on Google Earth, but the researchers did not have the opportunity to analyze and document this building in detail. Table 1 presents

exterior views of the 19 visited facilities. Facilities 13, 14, and 15 are presented in a single photograph.

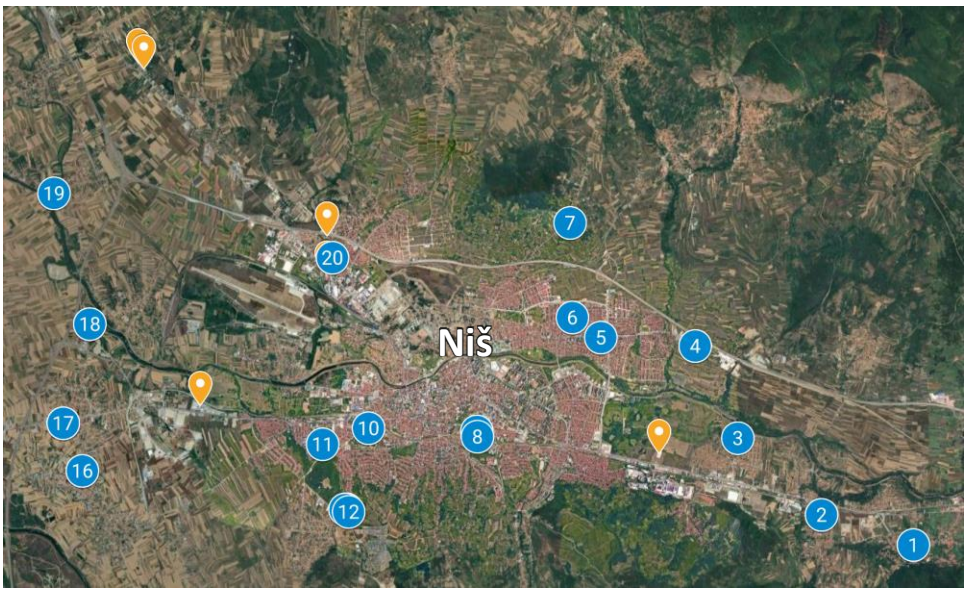

Figure 1: Locations of textile-covered sports facilities in Niš (based on Google Earth)

The discussion of the existing textile-covered sports facilities is conducted with respect to several aspects, including location, ownership, structural system, permanence, structural condition, and function. Among the visited facilities, six are located in the city, five are on the outskirts, and eight are in surrounding settlements and villages. These buildings are usually completely free-standing or, in some cases, connected to other buildings and annexes. Buildings 8 and 9 are located close to each other but are completely independent. Buildings 12, 13, 14, and 15 are part of the same sports complex, although building 12 is separate from the others. The remaining three buildings are positioned next to each other and connected along their longer sides.

With regard to ownership, several cases are present. Eight buildings are constructed on the grounds of primary schools in order to provide gym facilities for students who did not previously have access to covered spaces for physical education. Some of these are rented after school hours, generating additional income. Nine facilities are privately owned and operate as commercial venues, offering rental options for individual athletes and sports clubs on an hourly basis. One facility is owned by the municipality of Niška Banja, and another is part of the sports center Čair; both operate according to schedules defined by their respective owners.

There are two basic subtypes of textile membrane structures: mechanically prestressed and pneumatically prestressed. Mechanically prestressed membranes require a rigid supporting

structure for stability. Depending on the membrane form, it can generally be concluded that structures with significant double curvature require fewer supports, whereas those dominated by single curvature require more. In pneumatic membrane structures, stability is achieved through differences in air pressure. These can be single-layered, where internal air pressure is higher, or multi-layered, where the pressure between layers is increased. In Niš, both mechanically and pneumatically prestressed textile roofs are present. Mechanically prestressed systems are dominant, with 18 such sports facilities identified. Only one existing facility (number 8) and facility 20 (now dismantled) belong to the pneumatic type. In both cases, simpler structural solutions are used, characterized by dominant single curvature and single-layer air-supported membranes.

Another way to categorize textile membrane roofs is by their permanence. Two primary categories exist: permanent and temporary. A third possibility is retractable roofs, which, although not uncommon globally, are more complex and financially demanding, typically requiring additional supporting structures. Such high-end solutions are not yet present in Niš. Permanence is closely related to the structural system: mechanically prestressed membranes are generally permanent, while pneumatically prestressed structures may be either temporary or permanent. In the local climate, pneumatic membranes are often used as temporary winter enclosures and dismantled during warmer months to allow open-air use. This was the case with facility 20, which was dismantled before it could be studied. It is expected that facility 8 will also be dismantled in April and reinstalled in late autumn.

Regarding function, the textile-covered sports facilities in Niš exhibit a moderate degree of diversity. Their function is primarily determined by the type of flooring rather than the roof structure. Three main types of flooring are used: artificial turf, clay, and hard surfaces. Artificial turf is used for indoor football fields, while clay is used exclusively for tennis courts. Hard surfaces, made from various materials, support sports such as basketball, volleyball, futsal, tennis, and handball. Adequate interior height is essential to accommodate these activities. Facility 9 is particularly notable, as it undergoes a seasonal transformation: the hard floor is replaced with an ice surface during winter, converting it into an ice-skating rink. Although examples exist elsewhere in Serbia of swimming pools covered with textile membranes, such cases are not present in Niš.

One unexpected finding relates to the structural condition of these facilities. Although most were constructed 10–15 years ago, a significant number exhibit serious damage. Facility 6 is completely out of use and lacks its textile cover. Facility 10 has a partially torn membrane, while facility 16 shows similar damage, with sections of the roof and both gable walls destroyed. Facility 19 has entirely lost its roof membrane, with only fragments of the textile walls remaining. In total, 4 out of the 19 surveyed facilities are non-operational due to severe structural damage. All of these are located within primary school complexes. Their condition has persisted for several years, and reconstruction has been anticipated but not yet realized. Historical evidence indicates that additional textile-covered sports facilities once existed in Niš but have since been removed. At the same time, new facilities are expected to be constructed in the near futu

Table 1: Exterior views of visited textile-covered sports facilities (authors' archive)

4. CONCLUSION

This research investigates existing textile membrane roofs used in sports facilities in the wider area of Niš. This building typology was selected due to its prevalence among textile

structures in the region. The primary goal of the study was to identify and document existing facilities to establish a foundation for more detailed future analysis. The list of facilities was compiled through interviews with athletes and online research. As a result, 20 buildings were identified within the study area and subsequently visited. However, one temporary structure was dismantled before the visit, so detailed data were collected for 19 facilities.

The results indicate that there is approximately one textile-covered sports facility per 13,000 inhabitants in the analyzed region. This paper presents their locations and exterior appearances, along with a systematic discussion of their main characteristics. It was determined that all facilities belong to relatively simple forms of textile membrane structures. Ownership is divided between private and public sectors; however, four publicly owned facilities have been severely damaged for an extended period. Most facilities are designed as permanent structures, while only two are seasonal installations used exclusively during winter. Their functions include indoor football, tennis, and various indoor sports such as basketball, futsal, handball, and volleyball. In one case, the facility is seasonally converted into an ice-skating rink.

This study is focused on a specific building typology and structural system. A key limitation is the lack of detailed data regarding the exact type of textile material used in each facility. The data collected in this phase will be further analyzed in subsequent stages of the research. Future work will include detailed evaluation of structural performance, functionality, thermal comfort, energy efficiency, and lighting conditions. The ultimate objective is to develop improved design solutions for textile-covered sports facilities, thereby enhancing their performance and promoting broader application of textile architecture in the region. Such a result would provide better conditions for athletes and spectators, as well as benefits for the owners of textile buildings.

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AN INTEGRATED FFM-4 FRAMEWORK FOR FLUID FLOW MODELLING IN TEXTILE PROCESSING AND ADVANCED MANUFACTURING

Scientific paper
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ABSTRACT: *Fluid flow modelling has become an essential engineering tool for improving manufacturing efficiency, product quality, and process sustainability across numerous industrial applications. In recent years, increasing attention has been devoted to the application of fluid mechanics principles and computational modelling techniques for optimizing manufacturing processes while reducing material consumption, energy use, and environmental impact. Among these applications, textile processing and advanced manufacturing technologies represent two important industrial sectors in which fluid flow plays a critical role in determining process performance and product characteristics. This paper presents a comprehensive review of fluid flow modelling in textile processing and advanced manufacturing technologies. The study discusses the fundamental principles of fluid mechanics and examines their application in textile dyeing, coating, finishing, printing, additive manufacturing, composite manufacturing, polymer processing, and industrial cooling systems. Current developments in Computational Fluid Dynamics (CFD), numerical modelling, and digital engineering tools are analysed with particular emphasis on process optimization, sustainability, and manufacturing efficiency. Based on the findings of the literature review, the authors propose the FFM-4 (Fluid Flow Modelling – Four Pillars) Framework, which integrates four complementary pillars for systematic fluid flow analysis in manufacturing systems: Fluid Properties, Flow Behaviour, Process Modelling, and Manufacturing Performance. The proposed conceptual framework provides a unified perspective for integrating fluid mechanics principles with modern manufacturing technologies while supporting sustainable production and interdisciplinary engineering applications. The proposed FFM-4 framework may serve as a conceptual foundation for future research focused on Computational Fluid Dynamics, Artificial Intelligence, Digital Twins, sustainability assessment, and intelligent manufacturing systems. Furthermore, it provides opportunities for strengthening the integration of fluid flow modelling across mechanical engineering, manufacturing technologies, and textile engineering.*

Keywords: *Fluid flow modelling; Computational Fluid Dynamics (CFD); Textile processing; Additive manufacturing; Sustainable manufacturing; FFM-4 framework.*

INTEGRISANI FFM-4 OKVIR ZA MODELOVANJE STRUJANJA FLUIDA U TEKSTILNIM PROCESIMA I SAVREMENIM PROIZVODNIM TEHNOLOGIJAMA

APSTRAKT: *Modelovanje strujanja fluida postalo je jedan od ključnih inženjerskih alata za unapređenje efikasnosti proizvodnih procesa, kvaliteta proizvoda i održivosti savremenih industrijskih sistema. Poslednjih godina sve veća pažnja posvećuje se primeni principa mehanike fluida i računarskog modelovanja u cilju optimizacije proizvodnih procesa, smanjenja potrošnje materijala i energije, kao i ublažavanja negativnih uticaja na životnu sredinu. Tekstilna industrija i savremene proizvodne tehnologije predstavljaju oblasti u kojima strujanje fluida ima značajnu ulogu u određivanju performansi procesa i kvaliteta finalnih proizvoda.U ovom radu dat je pregled primene modelovanja strujanja fluida u tekstilnim procesima i savremenim proizvodnim tehnologijama. Analizirani su osnovni principi mehanike fluida, kao i njihova primena u procesima bojenja, oplemenjivanja, premazivanja i štampe tekstila, aditivnoj proizvodnji, proizvodnji kompozitnih materijala, preradi polimera i industrijskim sistemima za hlađenje. Posebna pažnja posvećena je razvoju računarske dinamike fluida (Computational Fluid Dynamics – CFD), numeričkom modelovanju i digitalnim inženjerskim alatima sa ciljem unapređenja optimizacije procesa, održivosti i proizvodne efikasnosti. Na osnovu sprovedenog pregleda literature, autori predlažu FFM-4 (Fluid Flow Modelling – Four Pillars) konceptualni okvir, koji integriše četiri komplementarna stuba za sistematsku analizu strujanja fluida u proizvodnim sistemima: osobine fluida, karakteristike strujanja, modelovanje procesa i proizvodne performanse. Predloženi konceptualni okvir pruža jedinstvenu perspektivu za povezivanje principa mehanike fluida sa savremenim proizvodnim tehnologijama, uz podršku održivoj proizvodnji i interdisciplinarnoj primeni u oblasti mašinstva i tekstilne industrije. Predloženi FFM-4 okvir može predstavljati konceptualnu osnovu za buduća istraživanja usmerena na primenu računarske dinamike fluida, veštačke inteligencije, digitalnih blizanaca, procene održivosti i inteligentnih proizvodnih sistema. Pored toga, okvir doprinosi jačanju integracije modelovanja strujanja fluida u mašinstvu, proizvodnim tehnologijama i tekstilnom inženjerstvu.*

Ključne reči: *Modelovanje strujanja fluida; Računarska dinamika fluida (CFD); Tekstilni procesi; Aditivna proizvodnja; Održiva proizvodnja; FFM-4 okvir.*

1. INTRODUCTION

The increasing complexity of modern manufacturing systems has significantly expanded the role of fluid flow analysis in industrial process optimization. Accurate modelling of fluid behaviour is essential for improving process efficiency, product quality, energy consumption, and resource utilization across numerous engineering applications [2,18].

From polymer extrusion and additive manufacturing to textile dyeing, coating, and composite processing, fluid flow directly influences manufacturing performance, process stability, heat transfer, and final product characteristics [8,11].
The textile industry is undergoing rapid transformation driven by digitalization, sustainability requirements, and advanced manufacturing technologies. Traditional textile processes such as dyeing, finishing, coating, and fiber production involve complex fluid flow phenomena that determine chemical transport, heat transfer, mass transfer, and material distribution [9,10].
Simultaneously, modern manufacturing technologies increasingly rely on Computational Fluid Dynamics (CFD), numerical simulation, and process modelling to optimize manufacturing parameters while minimizing material waste and environmental impacts [16,17].
In advanced manufacturing, fluid flow modelling has become an indispensable engineering tool for analysing molten polymer behaviour during additive manufacturing, resin impregnation in composite processing, cooling system performance, lubrication mechanisms, and thermal management [8,11,12].
Although numerous studies investigate fluid flow within individual manufacturing processes, limited attention has been given to integrating textile processing and advanced manufacturing technologies within a unified perspective. Establishing such a connection is particularly important as sustainable manufacturing increasingly combines digital engineering tools with process optimization to improve resource efficiency, product quality, and environmental performance [4].
The aim of this paper is to review the role of fluid flow modelling in textile processing and advanced manufacturing technologies, highlighting common fluid mechanics principles, current industrial applications, and future research opportunities. Particular attention is given to sustainable manufacturing, computational modelling approaches, and the integration of fluid flow analysis across engineering and textile production systems.

2. FUNDAMENTALS OF FLUID FLOW IN MANUFACTURING SYSTEMS

Fluid flow represents one of the fundamental physical phenomena governing numerous manufacturing processes. The movement of liquids and gases directly influences heat transfer, mass transfer, pressure distribution, and material transport, thereby affecting process efficiency, product quality, and manufacturing reliability. Consequently, understanding fluid flow behaviour has become essential for designing and optimizing modern industrial production systems [2,18].
Fluid behaviour is commonly classified as either laminar or turbulent, depending on the Reynolds number, which represents the relationship between inertial and viscous forces within the flowing medium. Laminar flow is characterized by smooth and orderly fluid motion with minimal mixing between adjacent layers, whereas turbulent flow exhibits chaotic velocity fluctuations and enhanced momentum and heat transfer. In manufacturing applications, both flow regimes are encountered depending on process conditions, fluid properties, and equipment geometry [7,18].

Among the most influential parameters governing fluid flow are viscosity, density, pressure, flow velocity, and temperature. These properties determine flow resistance, pressure losses, and energy consumption while simultaneously influencing transport phenomena within manufacturing systems. In polymer processing and textile finishing operations, viscosity variations caused by temperature changes may significantly affect process stability, coating uniformity, resin impregnation, and material deposition quality [2,11].

The rapid development of computational modelling techniques has considerably improved the understanding of fluid flow behaviour in industrial applications. Computational Fluid Dynamics (CFD) enables numerical prediction of velocity fields, pressure distribution, turbulence intensity, heat transfer, and material transport before physical implementation of manufacturing processes. As a result, CFD has become an indispensable engineering tool for optimizing equipment design, reducing production costs, minimizing energy consumption, and improving process efficiency across numerous manufacturing technologies [16,18].

In both textile processing and advanced manufacturing technologies, fluid flow modelling provides valuable information for optimizing manufacturing parameters and improving product performance. Whether analysing dye penetration into textile structures, molten polymer extrusion during additive manufacturing, resin flow in composite processing, or cooling performance in industrial equipment, the underlying principles of fluid mechanics remain fundamentally identical. Therefore, fluid flow modelling represents a common engineering approach that connects various manufacturing technologies through shared physical principles.

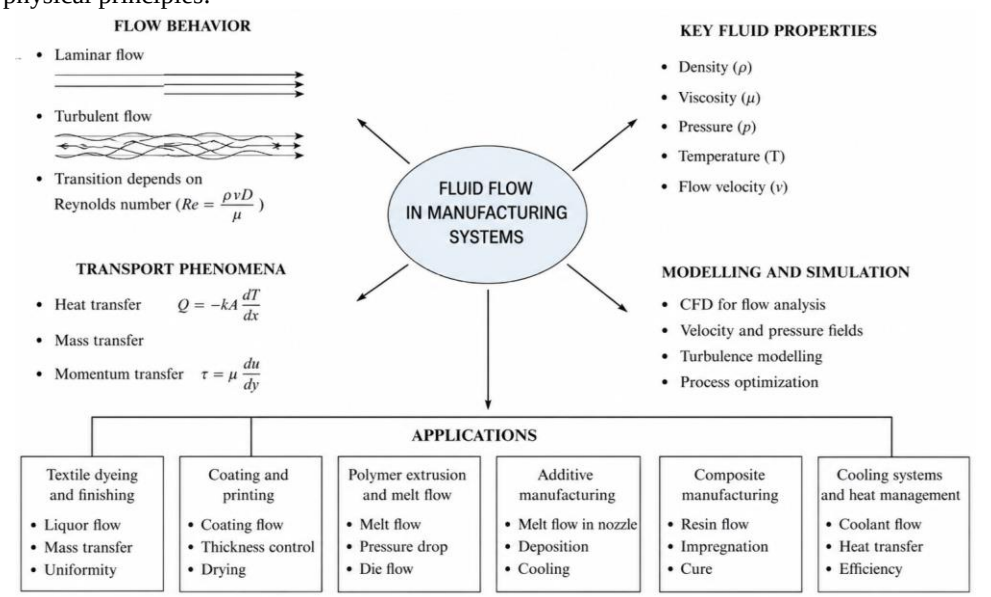

Figure 1: Fundamental fluid flow phenomena influencing manufacturing processes

3. FLUID FLOW APPLICATIONS IN TEXTILE PROCESSING

Fluid flow plays a fundamental role in numerous textile manufacturing processes, directly influencing product quality, process efficiency, resource consumption, and environmental performance. During textile production, liquids and gases are continuously involved in fiber formation, dyeing, finishing, coating, printing, washing, drying, and chemical treatment. The effectiveness of these processes largely depends on the controlled transport of fluids, heat, and dissolved chemical substances throughout textile structures [9,10].

One of the most important applications of fluid mechanics in the textile industry is dyeing, where the penetration and distribution of dye liquor determine color uniformity, dye fixation, and process efficiency. Proper control of flow velocity, pressure, temperature, and mixing conditions enhances mass transfer between the dye solution and textile fibers while reducing water, chemical, and energy consumption [9].

Fluid flow is equally important in textile finishing, where various chemical agents are applied to improve mechanical, thermal, or functional properties of fabrics. Processes such as padding, coating, impregnation, and washing require uniform fluid distribution to ensure consistent treatment over the entire textile surface. Poor flow control may result in uneven coating thickness, non-uniform chemical penetration, or defects that negatively affect product quality [10].

Modern textile printing technologies also rely on accurate fluid flow behaviour. The rheological properties of printing inks, nozzle design, droplet formation, and substrate interaction determine printing accuracy, color reproduction, and production efficiency. Numerical modelling and Computational Fluid Dynamics (CFD) are increasingly used to optimize ink transport, droplet deposition, and drying behaviour while minimizing material waste and process variability [17].

In recent years, sustainability considerations have significantly increased the importance of fluid flow optimization within textile manufacturing. Reducing water consumption, improving chemical utilization, minimizing wastewater generation, and enhancing energy efficiency have become primary objectives for modern textile production systems. Consequently, fluid flow modelling has evolved into an essential engineering tool for supporting environmentally responsible textile manufacturing and facilitating the transition toward more sustainable industrial processes [3,13].

Table 1: Fluid flow applications in textile manufacturing processes

Textile process	Role of fluid flow	Main objective
Dyeing	Dye transport and penetration	Uniform coloration
Finishing	Chemical distribution	Surface modification
Coating	Coating flow control	Uniform layer thickness
Textile printing	Ink flow and droplet formation	Printing accuracy
Washing	Water circulation	Contaminant removal
Drying	Air flow and heat transfer	Moisture removal

4. FLUID FLOW IN ADVANCED MANUFACTURING TECHNOLOGIES

Advanced manufacturing technologies increasingly rely on fluid flow modelling to improve production efficiency, process stability, product quality, and resource utilization. Although these technologies differ in terms of manufacturing principles, many of them involve similar fluid mechanics phenomena associated with molten materials, liquid resins, cooling media, lubrication systems, and heat transfer. Consequently, fluid flow analysis has become an essential engineering tool for process optimization across numerous industrial applications [16,18].

4.1 Additive Manufacturing

Among advanced manufacturing technologies, additive manufacturing represents one of the most significant applications of fluid flow modelling. During material extrusion processes such as Fused Deposition Modelling (FDM), molten polymer flows through the printer nozzle before being deposited layer by layer to form the final component. The rheological behaviour of the polymer, extrusion pressure, nozzle geometry, deposition velocity, and cooling rate strongly influence dimensional accuracy, interlayer bonding, mechanical performance, and surface quality of printed parts [8,12].

Numerical simulation and Computational Fluid Dynamics (CFD) have increasingly been applied to investigate melt flow behaviour inside extrusion nozzles, optimize printing parameters, and improve thermal management during layer deposition. These approaches contribute to higher process reliability, reduced material waste, and improved energy efficiency while supporting sustainable manufacturing strategies [6,8].

4.2 Composite Manufacturing

Fluid flow modelling is equally important in composite manufacturing processes, particularly during resin transfer moulding (RTM), vacuum-assisted resin infusion (VARI), pultrusion, and filament winding. In these processes, resin flow determines fibre impregnation quality, void formation, curing behaviour, and the final mechanical properties of composite structures. Accurate prediction of resin distribution enables improved process control while reducing manufacturing defects and material losses [11].

Advanced numerical models are widely used to predict resin filling time, pressure distribution, permeability effects, and temperature evolution during composite processing. Such simulations assist engineers in optimizing mould design and manufacturing parameters while improving production efficiency and structural performance [11,16].

In addition to resin filling analysis, fluid flow modelling plays a crucial role in predicting resin permeability through fibre reinforcements and evaluating the influence of processing parameters on composite quality. Parameters such as resin viscosity, injection pressure, fibre architecture, mould geometry, and temperature significantly affect resin infiltration and the formation of dry spots or voids within composite structures. Accurate numerical prediction of these phenomena enables engineers to optimize manufacturing conditions, reduce production defects, and improve the repeatability of composite manufacturing processes. Furthermore, coupling fluid flow simulations with curing kinetics and thermal

analysis provides a more comprehensive understanding of process behaviour, allowing improved control of dimensional accuracy, mechanical properties, and overall manufacturing efficiency. Consequently, integrated numerical modelling has become an important engineering approach for developing high-performance composite components used in aerospace, automotive, marine, and advanced engineering applications [1,11,16].

4.3 Cooling and Thermal Management Systems

Fluid flow also plays a crucial role in industrial cooling and thermal management systems. Efficient circulation of cooling fluids is essential for maintaining stable operating temperatures in manufacturing equipment, extrusion systems, injection moulding machines, and additive manufacturing devices. Proper heat removal improves dimensional stability, extends equipment lifetime, and reduces energy consumption during production [2].

The integration of CFD simulations into cooling system design enables engineers to analyse temperature distribution, coolant velocity, pressure losses, and heat transfer efficiency before physical implementation. As a result, computational modelling has become an indispensable tool for designing sustainable manufacturing systems with improved thermal performance and reduced operational costs [18].

Table 2: Comparison of fluid flow characteristics in advanced manufacturing technologies

Technology	Working fluid	Main fluid flow phenomenon	Engineering objective
Additive manufacturing	Molten polymer	Melt flow through nozzle	Printing accuracy
Composite manufacturing	Liquid resin	Resin impregnation	Void-free structures
Polymer extrusion	Polymer melt	Pressure-driven flow	Dimensional stability
Cooling systems	Coolant	Forced convection	Heat removal
Textile coating	Liquid coating	Surface flow distribution	Uniform coating
Resin Transfer Moulding (RTM)	Thermoset resin	Resin impregnation through fibre preform	Uniform impregnation and void reduction

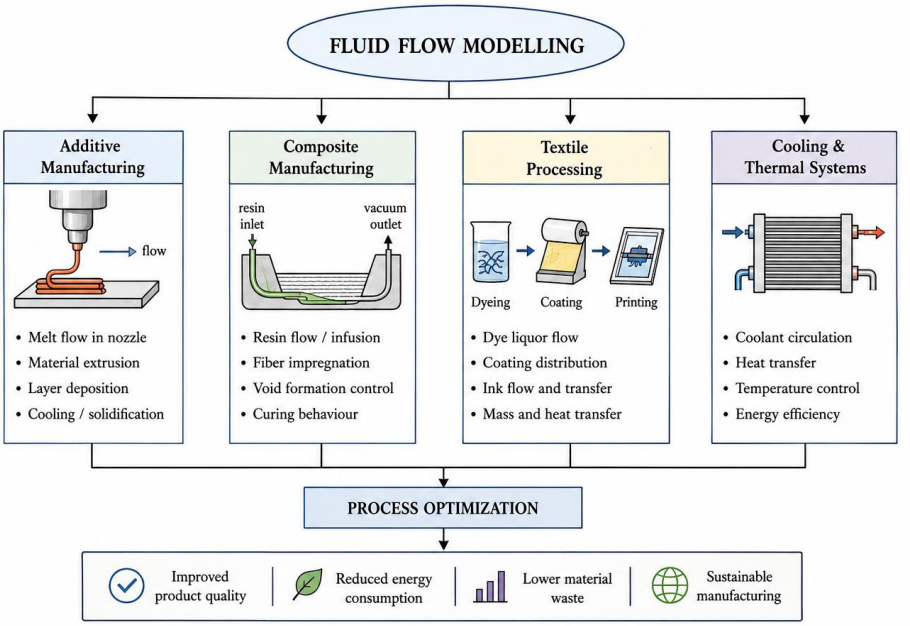

Figure 2: Integration of fluid flow modelling across advanced manufacturing technologies

5. PROPOSED FFM-4 FRAMEWORK FOR FLUID FLOW MODELLING IN MODERN MANUFACTURING

Based on the literature reviewed in the previous sections, it is evident that fluid flow modelling represents a common engineering approach connecting textile processing and advanced manufacturing technologies. Although fluid mechanics principles are applied in diverse industrial sectors, existing studies generally focus on individual manufacturing processes rather than providing an integrated perspective that combines textile production with advanced manufacturing systems. This observation highlights the need for a conceptual framework capable of systematically organizing the key elements influencing fluid flow analysis across modern manufacturing technologies [8,16,18].

To address this gap, the authors propose the **FFM-4 (Fluid Flow Modelling – Four Pillars) Framework,** which integrates four complementary pillars representing the essential components of fluid flow modelling in manufacturing systems. The proposed framework is intended to provide a systematic basis for understanding the interactions between fluid mechanics, computational modelling, manufacturing processes, and process performance while supporting future research in sustainable manufacturing.

The first pillar, **Fluid Properties,** includes the physical characteristics governing fluid behaviour, such as viscosity, density, pressure, temperature, and flow velocity. These

parameters directly influence transport phenomena, pressure losses, heat transfer, and material movement within manufacturing systems.

The second pillar, **Flow Behaviour,** describes the characteristics of fluid motion, including laminar and turbulent flow regimes, Reynolds number, momentum transfer, heat transfer, and mass transfer. Understanding these mechanisms is essential for predicting process stability and manufacturing efficiency.

The third pillar, **Process Modelling,** represents the integration of Computational Fluid Dynamics (CFD), numerical simulations, mathematical modelling, and digital engineering tools for analysing fluid behaviour before industrial implementation. These modelling approaches enable virtual process optimization while reducing development costs and experimental trials [17,18].

The fourth pillar, **Manufacturing Performance,** focuses on the practical outcomes of fluid flow optimization, including improved product quality, higher production efficiency, lower energy consumption, reduced material waste, enhanced sustainability, and optimized process control. These improvements contribute to more reliable and environmentally responsible manufacturing systems applicable to both engineering and textile industries [3,6].

The proposed FFM-4 framework demonstrates that fluid flow modelling should not be considered merely a computational analysis tool but rather an integrated engineering methodology capable of supporting process optimization across multiple manufacturing technologies. By connecting fluid mechanics principles with digital modelling and industrial applications, the framework establishes a unified perspective for future developments in sustainable manufacturing.

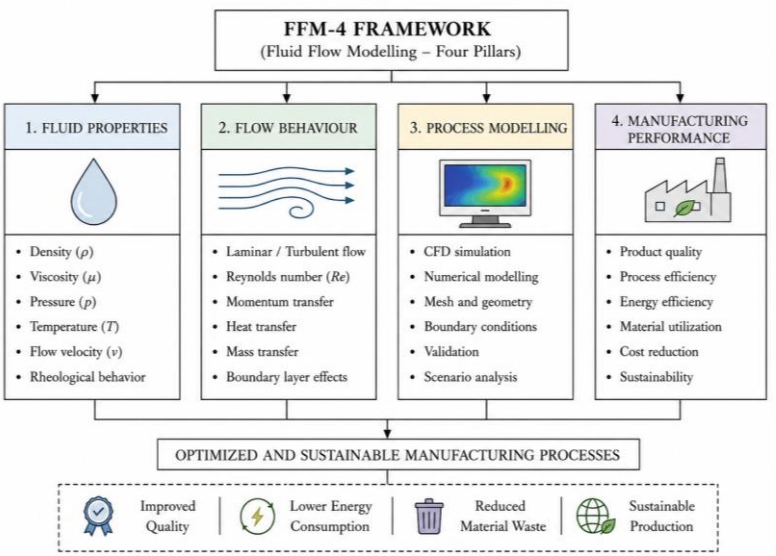

Figure 3: Proposed FFM-4 framework for integrating fluid flow modelling into modern manufacturing systems

6. FUTURE RESEARCH DIRECTIONS

The rapid evolution of manufacturing technologies is expected to further expand the role of fluid flow modelling in industrial process optimization. Future research should focus on developing more accurate numerical models capable of simultaneously describing fluid flow, heat transfer, material behaviour, and process interactions within increasingly complex manufacturing environments. Such integrated approaches will contribute to higher prediction accuracy while reducing experimental costs and accelerating industrial implementation [16].

One of the most promising research directions involves the integration of Computational Fluid Dynamics (CFD) with artificial intelligence (AI) and machine learning (ML) techniques. Data-driven models can significantly improve process prediction, parameter optimization, and real-time decision-making by combining numerical simulations with experimental and industrial data. These technologies are expected to play an increasingly important role in intelligent manufacturing systems and digital production environments [4].

The concept of Digital Twins also represents an important opportunity for future manufacturing systems. By combining real-time process monitoring with fluid flow simulations, Digital Twins enable continuous optimization of manufacturing operations, predictive maintenance, and adaptive process control. Such approaches may substantially improve manufacturing flexibility while supporting sustainable production and resource-efficient process management [15].

Another important research direction concerns the integration of fluid flow modelling with Life Cycle Assessment (LCA)and multi-criteria decision-making (MCDM) methods. Combining numerical simulations with sustainability assessment techniques may support the selection of environmentally friendly manufacturing strategies, optimized process parameters, and sustainable material alternatives. Decision-support methods such as the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) could further assist engineers in evaluating manufacturing alternatives according to technical, economic, and environmental criteria [5,10,14].

Future investigations should also emphasize sustainable textile manufacturing, additive manufacturing, and composite processing by reducing water consumption, improving energy efficiency, minimizing material waste, and enhancing process reliability through advanced fluid flow modelling. These efforts are fully aligned with the principles of Industry 5.0 and the transition toward sustainable and digitally connected manufacturing systems [4,6].

7. CONCLUSION

Fluid flow modelling has become an essential engineering tool for understanding, analysing, and optimizing modern manufacturing processes. As demonstrated throughout this review, the principles of fluid mechanics are widely applied across both textile processing and advanced manufacturing technologies, including additive manufacturing,

composite manufacturing, polymer processing, and industrial cooling systems. Although these manufacturing technologies differ in their operational characteristics, they share common fluid flow phenomena that significantly influence process efficiency, product quality, energy consumption, and material utilization [8,18].

The literature review indicates that numerical modelling and Computational Fluid Dynamics (CFD) have considerably improved the capability to predict fluid behaviour, optimize manufacturing parameters, and reduce experimental efforts during process development. The increasing integration of digital engineering tools with manufacturing technologies further supports sustainable production by improving resource efficiency and reducing environmental impacts [6,16].

As the principal contribution of this study, the authors proposed the FFM-4 (Fluid Flow Modelling – Four Pillars) Framework, which integrates four complementary pillars: Fluid Properties, Flow Behaviour, Process Modelling, and Manufacturing Performance. Unlike existing studies that primarily focus on individual manufacturing technologies, the proposed framework provides a unified conceptual perspective for integrating fluid flow modelling across textile processing and advanced manufacturing systems.

The proposed framework may serve as a conceptual basis for future investigations involving Computational Fluid Dynamics, Artificial Intelligence, Digital Twins, and sustainability assessment methodologies. Furthermore, it may facilitate interdisciplinary collaboration between mechanical engineering, manufacturing technologies, and textile engineering while supporting the development of more efficient, sustainable, and digitally integrated production systems [4].

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9. Međunarodna naučna konferencija
„**Savremeni trendovi i inovacije u tekstilnoj industriji**“
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DEVELOPMENT AND IMPLEMENTATION OF QUALITY CONTROL METHODS IN TEXTILE PRODUCTION

Review paper
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ABSTRACT: *The importance of planning, monitoring and controlling textile production determines the efficiency, quality and allocation of resources, so that it is compared to earlier procedures, which depended on raw material bases, production technologies and the involvement of people, while modern processes increasingly rely on information technologies and connected supply chains. The inclusion of sensors, RFID, tags, software and analytical programs allows to achieve qualitative indicators for the most acceptable textiles, which meet the demands of consumers as well as certified bodies for sustainable materials. The production of textiles is carried out in factories, but without standardized processes of material transfer, processing and control, it is not possible to achieve the set goals, among which the monitoring of raw materials, the use of resources, before, during the transformation and after the use of textiles, plays a significant role, considering the ecological perspective. The paper presents the analytical-methodical procedure of applying existing methods of textile quality control, along with scientific methods that suggest the use of modern technologies, software and tools.*

Keywords*: quality control, methods, modern technologies, testing, textiles.*

RAZVOJ I IMPLEMENTACIJA METODA KONTROLE KVALITETA U PROIZVODNJI TEKSTILA

APSTRAKT: *Važnost planiranja, praćenja i kontrolisanja proizvodnje tekstila uslovljava efikasnost, kvalitet i raspoređivanje resursa, tako da se upoređuje sa ranijim postupcima, koji su zavisili od sirovinskih baza, proizvodnih tehnologija i uključenosti ljudi, dok se u savremenim procesima sve više oslanja na informacione tehnologije i povezane lance snabdevanja. Uključenost senzora, RFID, tagova, softvera i analitičkih programa omogućava da se ostvare kvalitativni pokazatelji za najprihvatljiviji tekstil, koji odgovara zahtevima potrošača kao i sertifikovanih tela za održive materijale. Proizvodnja tekstila se obavlja u fabričkim pogonima, ali bez standardizovanih procesa prenosa materijala,*

obrade i kontrole nije moguće postizanje zadatih ciljeva, među kojima značajnu ulogu ima praćenje sirovina, upotreba resursa, pre, u toku transformacije i nakon upotrebe tekstila, s obzirom na ekološku perspektivu. U radu se predstavlja analitičko-metodički postupak primene postojećih metoda kontrole kvaliteta tekstila, uz naučne metode kojima se predlaže korišćenje savremenih tehnologija, softvera i alata.

Ključne reči: *kontrola kvaliteta, metode, savremene tehnologije, ispitivanje, tekstil.*

1. INTRODUCTION

Production activity is complex because it consists of the preparation of production, the execution of production and the control of production. Production preparation includes technical preparations and organization for the normal course of the production process. The measure of preparation includes design, construction, innovation and reconstruction, as well as the specification of the technological process. The production itself should include the process of transformation of input elements into output elements, which includes the control of the receipt of raw materials, and finally the control of the output, i.e. the final product.

The quality of the product should meet the standards as well as the expectations of the user. Through control, defects are noticed, which were caused by the wrong elaboration of the technological process, wrong construction, with the wrong built tool or the use of materials. In the past, quality control was administrative and included the scope of work within the set technical characteristics, the method of control with the help of a measuring tool and the organization of an independent controller. The key position in the quality policy is in the development function. In order to achieve the highest possible level of product quality, the greatest value is the area of development, process planning and finally production. Although it is the most important development function, its costs amount to 10-20% of revenue, and the impact on profitability increases to 80-90%.

Production quality control planning involves defining key parameters that ensure that products meet the prescribed standards. Control planning includes determining the place and time of control (input raw materials, intermediate stages, finished product), choosing methods and instruments, defining the scope of control (sampling or 100% control) and the holder of control activities.

The development of quality control in production has evolved from passive verification of finished products to modern, automated systems. Today, this process focuses on error prevention and optimization. The key stages in development are verification (focus on end product inspection and scrap removal), statistical process control (SPC - monitoring of parameters during production using statistical methods), integrated management systems (TQM, ISO 9001 - quality is the concern of the entire organization), Industry 4.0 - application of digital technologies, artificial intelligence (AI) and computer vision for automated detection of errors in real time.

2. SPECIFICS OF TEXTILE PRODUCTION AND STANDARDIZATION

Textile products are made from various raw material sources, so fibers, yarn, thread or fabrics, are used to make finished products. Natural fibers have no major use, while man-made fibers dominate the nonwoven industry with a 90% share of use [1, 2, 3]. Wearable textiles include classic and fashionable items for intimate purposes, sports or protective equipment [4], and for these reasons are the basis for checking for harmful substances, colors and odors. Non-wearable textiles are used as bedding, tablecloths or pillows, which come into contact with the body, while technical textiles do not have a direct impact on humans. Textile production is a complex activity that causes harmful effects on the environment and then on humans. By 2030, the global textile industry is expected to use 50% more water, emit 63% more carbon dioxide and produce 62% more waste than in 2015. It is estimated that by 2050, with the current trend of textile production, population growth, and the discarding of non-recycled clothing, there will be major problems with solid textile waste [6].

All textile products that are manufactured must rely on strategic intentions to meet the needs and meet quality standards in the receipt of raw materials, processing and control of finished products. Textile products in the fashion industry have the ability to assess quality through the fineness of the material, applying standards for storage, ironing, maintenance, long-term use and potential recycling. In the control processes, the characteristics of bleaching agents, hand or machine washing at a defined temperature, ironing, selection of clothes by composition, duration of washing, length of drying, etc. are considered. Consumers want there to be uniform rules that apply to the maintenance of clothing or treatment with different chemicals. In order for textile products to be placed on the EU market, fibre composition labels are required. National authorities check the conformity of textile products with labels at the stages of the chain from the submission of the request for customs clearance to the storage of distributors in wholesalers or smaller retail chains.

The General Product Safety Regulation (GPSR) covers consumer products and mandates that safe products can be placed on the EU market. There are several standards related to textile products, such as EN 14682, EN 13209-1 and EN 13209-2, which relate to the safety of children's clothing, childcare products (frame carriers) and child care products (soft carrier). The Global Organic Textile Standard (GOTS) provides a credible guarantee to consumers from the collection of raw materials, environmentally and socially responsible production to labeling. The Fair-Trade Textile Standard includes an innovative approach to insurance to address weaknesses in the conformity audit model for the textile industry, with guaranteed fibres that are within the framework of the schemes for the environment, socio-economic criteria and the scheme management system. OEKO-TEX® STANDARD 100 is a label for textiles tested for harmful substances. ASTM Textile Standards provide specifications for the physical, mechanical, and chemical properties of textiles, woven fabrics, and woven fabrics, as well as natural and man-made fibers. ECO Textile - ECOmark® is the world's leading standard for the processing of textile products made from organic fibers. It defines environmental protection criteria throughout the organic textile

supply chain, respecting social criteria [7]. Consumers must be sure that the textile item is safe to use and meets the required standards.

3. THE NEED FOR MEASUREMENT AND CONTROL

Ensuring accurate measurement results implies timely organization of activities, but the basis is the correct measurement equipment. It is necessary to calibrate or verify the equipment at the selected time, so that it is monitored, before, during and after use. According to the assessment, the measuring equipment is adjusted, and the identification is enabled by the calibration status. In the end, protection is done so that the results are not wrong, and then it also protects against damage.
Manufacturing companies should plan and monitor processes, measurements and improvements to demonstrate product compliance, ensure the compliance of the quality management system, and continuously improve the effectiveness of the quality management system.
In order to improve the characteristics of the product, it is necessary to have reliable information, human resources that are trained, and know how to use methods for analysis and decision-making, there are programs that support BigData analytics in the use of modern methods and techniques of continuous improvement.

3.1 Monitoring product characteristics

In production, there is technical documentation, which provides insight into the level of quality and reliability of the product. When the product has the intended properties from the documentation, then the planned level of quality has been achieved. The ratio of the desired quality for the user and the one that is consistent with the manufacturer's projection depends on influential factors such as raw materials, means of work, method of work, production conditions and the human factor [8]. In the case of textile products, as an area that is variable due to trends in clothing, there must be a correspondence between the expected and actual characteristics of the material. As a raw material in textile products, it is necessary to test and assess quality at the entrance, because the transformation of a bad raw material will place a garment of poor quality.
Sometimes the same machine does not contribute to the production of an equally high-quality product, because it needs to be maintained. In dealing with technology, there are many methods of work, but companies need to find the most optimal methodology. The best effects in production are achieved in ambiently decorated spaces, halls with air conditioning, illuminated and safe, which as a condition of work contributes to satisfaction. In the textile industry, air humidity has a greater impact than in the production of Tetra Pak products. If the work is done in the morning, it can be of better quality compared to the work done at night or at the end of the week. Man has a specific attitude towards work, and his qualities affect the quality of work, production and all the mentioned groups of factors. Figure 1 shows a model of the operational phases of quality control, starting with the input control, all the way to the control of work equipment.

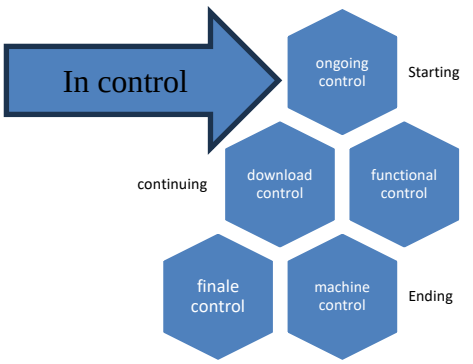

Figure 1: Model of Operational Phases for Quality Control

In complex production processes, there is a need for final control to take place when moving to the second technological stage. Some manufacturing industries have three processes, some five or ten, so each must have process quality control and final quality control. Final quality control is carried out in the case of checking the functionality of products, in expensive products, in products intended for human health and safety, as well as in the case of expected non-conformities or in individual production. Statistical control is performed in all other cases.

Quality is checked by internal or external auditors by focusing attention on the quality system or some segment of it. Verification includes regulations about what needs to be done, what is currently being done and what needs to be done.

Product quality assurance relies on records and documents of results. Verification through results refers to the design phase when models are calculated and made, simulations, as well as in the implementation phase when there are many measurement results of parts of assemblies, etc. Verification in relation to resources, used to strengthen qualities such as people, equipment and methods.

According to ISO 9004, there are tools for improving quality systems in numerical areas such as control charts, histograms, Pareto diagram (ABC) and scatter diagram. These tools are graphically represented to diagnose the problem and suggest an appropriate computational approach in the statistical diagnosis of the problem.

As in the technological world and the latest Industry 5.0, it is implied by the use of sustainable work methods and the application of BigData and RFID technologies, we recognize that the Japanese style of quality control is profiled with the achievement of all results with 100% effects. The new concept of quality in Japan consists of: 1) Kanban – visual record; 2) Hoshin-Kanri – policy management; 3) Kaizen – promotion.

In addition to these, there are also 5S (seiri-organization; seiton-orderliness; seiso-purity; seiketsu-standardization; Total Production Maintenance-TPM, Quality-Managed Circulars-QCC, Quality Function Development-QFD, Cause & Effect Diagram-CE, Just-in-time Production Management System.

4. APPROACH TO QUALITY CONTROL IN THE TEXTILE INDUSTRY

A very important starting point for quality control is an organized workforce that will keep up with the changes. The production plan controls the production schedule and ensures that the products are delivered on time. Formulated by the production planning department, the production process plan (Figure 2) should coordinate the parts of the fabric department, garment sampling, cutting and other departments.

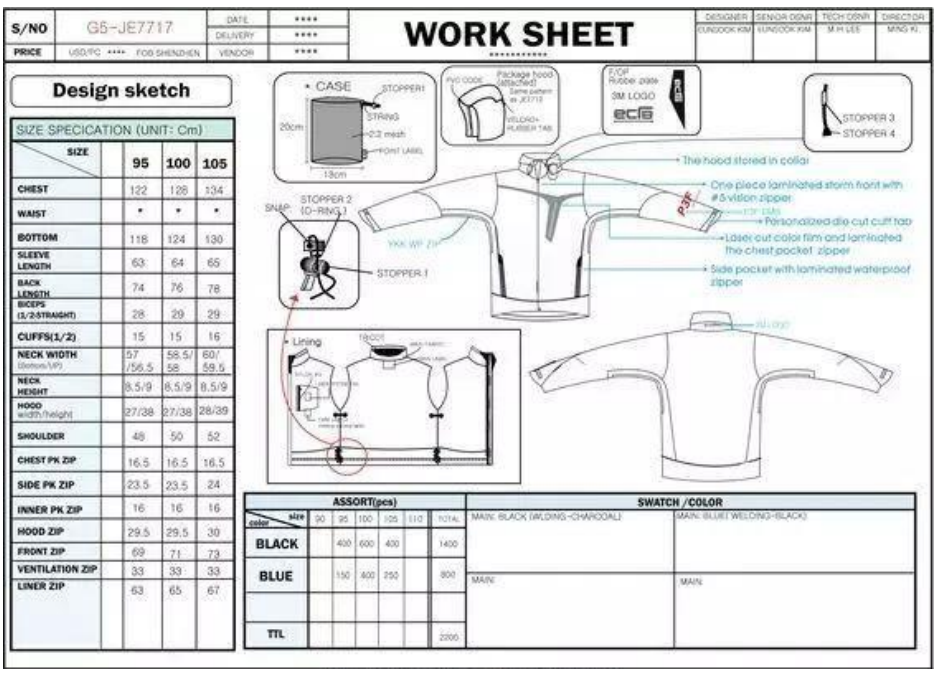

Figure 2: List of production process [9]

The craft sheet contains pictures that show a pattern of fabric accessories. This document allows the manufacturer to record the requirements and precautions. Information about the design and requirements of the production process should be included in the production plan.

4.1 Integrated Quality Control System in the Textile Industry

A quality management system (QMS) is a structured framework designed to standardize, monitor, and improve an organization's processes, especially in areas such as quality control in the apparel industry. The implementation of effective quality control in the textile industry requires an approach that includes raw materials, production processes and final checks. By conducting standardized tests, errors are eliminated and the percentage of waste is reduced.

The key stages of the implementation of quality control methods include:

1. Raw material control: Analysis of fibers, yarns and fabrics in laboratories (testing for color fastness, wear resistance and tear resistance).
2. Process control: Monitoring of production parameters (machine adjustment, control of thread tension and seam evenness) in order to detect defects in time.
3. Statistical Methods (SPC): The application of scientific and statistical methods for the analysis of samples at the various stages of garment making.
4. Final Inspection: A thorough check of the final garments against industry standards (e.g. AQL tables for an acceptable level of quality).

Upon receipt of purchased goods, there is quality control at the entrance that examines raw materials, semi-finished products, finished products and devices. After the input control, we move on to ongoing or inter-phase control that examines the quality during the manufacturing process. The final or control of the takeover is carried out after the completion of the technological phase of work. Functional control checks the functionality of the product in addition to assembly. Output quality control is the final check of the joining, packaging and shipping of finished products. Control of work equipment is important because of the production and exploitation of work equipment.

The tasks of quality control of the input material include all purchased raw materials, which requires their own laboratories or contracted relationships for testing. In the case of input materials, it is expected to control the quality of raw materials, materials, semi-finished products and finished parts coming from the side, testing of chemical composition, spectrometric or physical properties, testing by defettoscopic methods, quality testing under thermal and surface treatment, improvement of laboratory testing, cooperation with state authorities and health services, maintaining professional relationships with suppliers.

The tasks of production quality control are:

- quality control (QC) during the production of the product.
- control of the discipline of technological processing,
- timely notification of anomalies in production.
- control of the correct storage of finished products,
- QC of assembly,
- QC of completion, packaging and shipping,
- monitoring the level of quality of finished products,
- QC of means of operation and determination of the capabilities of machines,
- monitoring the quality of work resources and more.

4.1.1 Quality testing of raw materials for textiles and textile products

Textile fibers are tested by various methods, in relation to the adopted standards in the organization, as well as business strategies on the placement of goods on the global market. Measurement of inputs (raw materials) in the textile industry involves checking the quality and dimensions before the start of production. This prevents mistakes and waste. The basic parameters to be measured include the physical and chemical properties of the material.

Laboratory devices and testing systems are used to check the most important parameters. The most important parameters are:

1. The fineness of the fibers, determined by the thickness of the strands. It is measured by precise weighing (mass per unit length) or acoustic methods.
2. The length of the fibers, affects the strength of the yarn. It is measured manually or with automatic optical instruments.
3. Strength and stretchability. It is measured by the tearing force on special dynamometers. It shows how durable the material is.
4. The moisture content of the raw material, as the textile fibers absorb water. It is measured by drying samples or electronic moisture meters.
5. Color fastness. It is checked how the raw material reacts to washing, light and friction.

The methods of measuring inputs in textile production are divided into laboratory (destructive and non-destructive) and process (line) methods, which are presented participatorily in Table 1. They ensure that the fibers, yarns or fabrics meet the standards before entering the plant.

Table 1: Test methods of fibers, yarns and fabrics, knitwear

Methods	**Sub-method**	**Explanation**
Fiber tests	Microscopy	Determination of the longitudinal shape and cross-section of fibers under a microscope to identify the composition.
	Gravimetry	Accurate measurement of the mass of the sample before and after drying to determine the actual moisture.
	Micronaire (air flow)	Measurement of the fineness of cotton fibers through the resistance to the passage of air into the compressed sample
	Photo-electro	The use of optical sensors to measure the length and length distribution of fibers, e.g. fibrograph
Yarn tests	Method of Winch and Scale	Winding a standard length of yarn on a winch and weighing to determine fineness
	Constant increment of force/length	Testing on dynamometers where the yarn is stretched to breaking
	Black table-visual method	Winding the yarn on a black backing to spot knots, thickenings, impurities
	Capacitive method (Uster test)	Passing the yarn through the measuring field of the capacitor to electronically register the unevenness of the mass
Fabric and knitwear tests	Cutting samples with a circular cutter	Sampling of the exact area (100 cm^2) and gram weighing to determine the surface mass (g/m^2)
	Optical Counting Method	Using a magnifying glass with a scale or digital drills to determine the density of wires
	Hydrostatic pressure method	Measurement of the resistance of materials to the penetration of water under pressure (in water-repellent and technical textiles).

4.1.2 Measurement of quality during the production of textile products

Methods of quality measurement in the production of textiles itself (during the process of processing and production of the finished product) focus on the early detection of defects, the stability of the machines and the control of the final characteristics of the product (Table 2). These methods combine visual, mechanical, automated, and statistical approaches.

Table 2: Methods of quality control of textiles during the process

Methods	**Sub-method**	**Explanation**
In-process control	Automated Optical Inspection (AIO)	High-resolution cameras and sensors are mounted on a loom or knitting machine. In real time, the material is scanned and the machine is stopped if there is a break in the wire, knot or hole.
	Electronic Tension Control	The tightness of the warp and weft due to weaving or yarn during knitting is constantly measured. Uniform tension prevents deformation of the structure of the textile.
	Control of finishing parameters (Online sensors)	Constant measurement of pH, chemical concentration, drying temperature and percentage of application during staining. Recognizing deviations allows for engagement and quick response.
Laboratory quality control	Wear resistance test (Martindale method)	The sample is subjected to circular friction under pressure to measure the resistance to clumping and abrasion
	Spectrophotometry (Measurement of Color Fastness and Difference)	The device measures the reflection of light from the surface of the fabric. A value of color deviation from the standard is obtained by computer, so that color melting and coloring are prevented.
	Dimensional Stability Test	Testing after a standardized wash-and-dry cycle (in %) to measure the shrinkage and expansion of the material.
	Tear and Puncture Test (Dynamometry)	Using the Elmendorf method and using a steel ball, the force required to split or puncture a material is measured.
Final inspection and sorting	Overview on light tables (Viewing tables)	Controllers manually release the fabric over an inclined backlit table. They are visually found and marked defects in weaving, dyed or with stains.
	Error scoring system (4-Point System)	ASTM D5430 standard that from 1-4 scores errors as penalty points depending on the length. If the linear meter exceeds the permissible number of points, the fabric receives a lower category (scrap or other class).

	Statistical quality control (SPC)	A control chart (X-bar and R charts) is used to track deviations in grams or roll width over time. The goal is to spot the awnings before the product comes out of the tolerance values.

4.1.3 Measurement of quality after the production process

Post-production quality measurement methods (final control) focus on confirming that the finished product meets technical specifications, aesthetic requirements, and safety standards before it is packaged and delivered to the customer (Table 3). These methods are applied to finished material (meters) or to finished garments/textiles.

Table 3: Methods of quality control after the production of textile products

Methods	**Sub-method**	**Explanation**
Visual methods and classification of errors	Overview on control tables	Fabric or knitwear is passed over illuminated vertical or inclined tables. The controller visually identifies errors in weaving, dyeing, printing, or finishing.
	A system of scoring or ASTM D5430, 4-Point System	Each visual error is awarded penalty points (1 to 4) based on length or size. The total number of points per 100 square meters determines whether the material is "first class" or scrap.
	Inspection of finished garments	Checking the symmetry of seams, the correctness of zippers, buttons, labels and the cleanliness of the entire product on mannequins or tables
Laboratory Performance Test Methods	Dimensional stability (washing and drying method)	The exact change in dimensions (shrinkage or expansion) is measured as a percentage after a standardized wash (usually according to the ISO 6330 standard).
	Pilling and abrasion resistance (Martindale & Pilling Box)	The pattern of the finished textile is rubbed against a standard woolen fabric. The number of cycles until the threads are torn or the level of formation of annoying "lumps" (peeling) is measured.
	Strength of seams and materials	Dynamometers measure the force required to break the seam or the material itself at the point of connection.
Methods of Verification of Stability and Chemical Safety	Spectrophotometry (shade control)	Digital measurement of light reflection to ensure that there is no color deviation (ΔE) between different rolls or pieces from the same series.
	Color fastness	Testing of samples for rubbing (dry and wet by means of *a crometer*), on light (xenon lamps) and on sweat, so that paint does not pass on skin or other clothes.
	Environmental and chemical control (OEKO-TEX/REACH)	Chemical analysis for the presence of prohibited substances (formaldehyde, heavy metals, azo dyes) that can cause allergies or be toxic.

Geometric and Functional Methods of Measurement	Dimension Control (Measurement Board)	In the case of finished clothing, the key points (chest circumference, sleeve length, waist) are measured with stencil rulers and ribbons and compared with the permissible deviations (tolerances) from the technical documentation.
	Functionality testing	Checking specific properties such as water repellency (spray test), vapour permeability (material breathability) or flame resistance (in protective clothing).

In the case of a laboratory method of performance testing or a destructive method, it should be emphasized that samples are taken from the finished batch and tested under laboratory conditions.

6. MODERN TOOLS AND SOFTWARE SUPPORT FOR QUALITY CONTROL

In today's textile industry, there is no single software that performs all the measurements on the machines on its own. There are two groups of software solutions that cover all three processes (before, during, and after production):

1. specialized textile ecosystems that connect laboratory hardware and production sensors,
2. MES/QMS systems, as well as software for production and quality management.

Specialized textile software comes from the manufacturer of the measuring equipment and communicates directly with the measuring instruments in all three phases. Table 4 shows the most commonly used software that have demonstrated advantages in terms of features and scope of benefits.

Table 4: Overview of specialized software to support textile quality control

Software	**Process**	**Explanation**
Uster Quality Expert (Uster Technologies)[10]	Pre-production	Analyzes data from *Uster Tester* and *Uster Fiberget* devices. It measures the fineness, length, and moisture of fibers and yarns before they enter the process.
	During the production	It connects to yarn cleaners on machines (online sensors). It monitors tension, interruptions and detects errors in real time.
	After Production	Generates final reports on the quality and uniformity of the finished yarn or fabric, defining its class.
BMSvision (Manufacturing Execution Systems for Textiles) [11]	Pre-production	The *QualiMaster module* receives data on the quality of the received raw materials from the database and plans their allocation to the machines.
	During the production	Monitors the operation of looms and knitting machines in real time using sensors. Detects a

		decrease in efficiency and technical errors in weaving.
	After Production	Software runs and manages automatic or manual viewing desks. Records error maps on rolls and automatically calculates points (4-Point System).
Barco Textiles (Sedo Treepoint / Barco)[12]	Pre-production	Manages the formulations of dyes and chemicals in the laboratory and verifies the spectral data of the input material.
	During the production	Monitors the dyeing, finishing and drying processes via sensors on the machines (pH, temperature, time)).
	After Production	Integrated with spectrophotometers, the software measures the ΔE (color deviation) of the finished textile and performs a software inspection of the fabric.

The second group of software, which is textile MES and QMS packages of quality data management programs. They collect, digitize, and analyze quality data from all three processes through digital lists, tables, and integration with measuring devices (Table 5).

Table 5: Overview of the MES/QMS program to support textile quality control

Software	**Process**	**Explanation**
Pivot88 (Leading cloud software) [13]	Pre-production	Digital input of material sample testing results (lab-dips, shrinkage tests, raw material composition check).
	During the production	The *In-line Inspection* module allows controllers to enter sewing or weaving errors via the tablet on the lines, creating real-time Pareto charts.
	After Production	It covers Final Inspection and AQL (Acceptable Quality Limit) statistical sampling of finished garments prior to packaging.
Inspectorio Sight [14]	Pre-production	Verification of the quality of fabrics and materials before cutting through digital laboratory reports.
	During the production	Monitoring operations in the plant and early detection of repeated errors on the sewing lines.
	After Production	Automated creation of quality certificates, inspection of finished goods based on images and data entered through the application, and risk prediction for future orders using artificial intelligence (AI).

The choice of software implies a good knowledge of the problems that occur, as well as a strategic basis for solving problems in defects in the textile industry. If the company carries out activities in the field of spinning, weaving or knitting, then the suggestion is to use Uster Quality Expert or BMSvision. The reason is the direct connection to the means of operation and the hardware for measurement. For companies engaged in ready-to-wear and

sewing of finished products, due to the digitization of the work of controllers and quality monitoring through all phases in the supply chain, the Pivot88 or Inspectorio program is shown.

6.1 Textile Testing and Quality Control Software Example

Textile testing and quality control software makes it possible to perform quality control in the apparel industry by automating complex processes and providing real-time insights. Tools such as the Tekmon QMS (Figure 3) allow manufacturers to conduct fabric tests, monitor production quality, and easily generate compliance reports. The advantage of this software is that formula-based validation and trend analysis reports are created. Thus, they help identify recurring problems, while mobile offline functionality from a distance ensures continuous inspections.

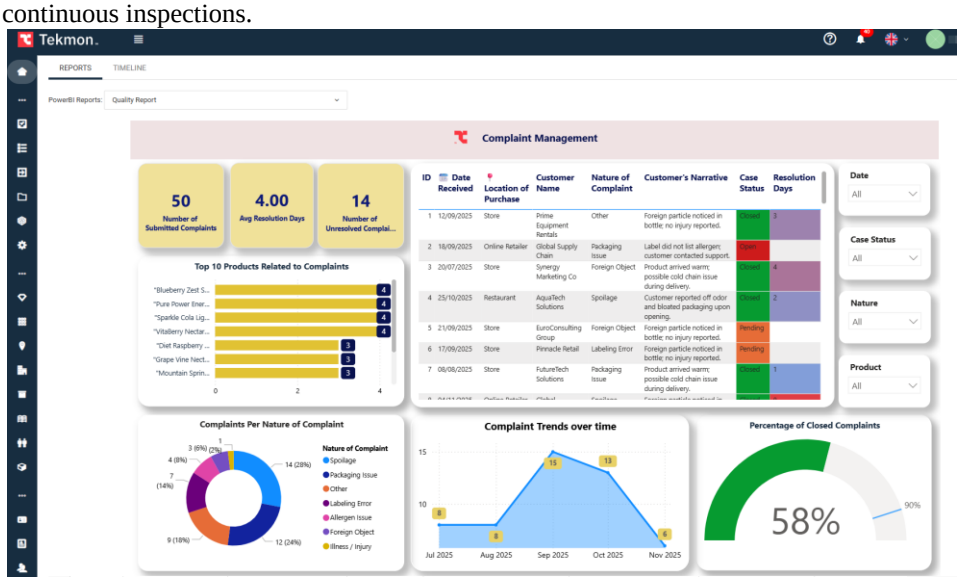

Figure 3. Layout of the Tekmon QMS package interface [15]

Manufacturers can streamline audits, manage supplier quality, resolve complaints, and ensure compliance with ease. With 15 key functionalities, Tekmon QMS - from real-time dashboards to customizable templates - empower businesses to improve quality, reduce costs, and maintain a competitive advantage.

7. CONCLUSION

The textile industry is a dynamic field in which quality control in the clothing industry is paramount. Ensuring high standards in clothing production not only meets customer expectations, but also complies with regulatory requirements and increases the brand's reputation. Quality control in the textile industry involves systematic processes to ensure

that textile products, from raw materials to finished garments, meet predefined standards. In the context of quality control in the apparel industry, it includes testing, inspections and corrective actions to eliminate defects and maintain consistency. Unlike quality assurance, which focuses on process improvement, quality control confirms that products adhere to specifications.

The basic steps in the application of quality control include the control of raw materials (fiber, yarns and fabrics analysis), process control (machine adjustments, testing of thread tension and seam evenness) using statistical methods and final inspection (check of the final garments against industry standards).

The methods of measuring inputs in textile production are divided into laboratory (destructive and non-destructive) and process (line) methods, which provide fiber test, yarn test and Fabric and knitwear tests. The methods of quality control of textiles during the process are In-process control, Laboratory quality control and Final inspection and sorting with theirs sub-methods. The methods of quality control after the production of textile products are Visual methods and classification of errors, Laboratory Performance Test Methods, Methods of Verification of Stability and Chemical Safety, and Geometric and Functional Methods of Measurement.

In the apparel sector, quality control is vital to address issues such as fabric defects, sewing errors, or size inconsistencies. By integrating advanced tools and software, manufacturers can increase efficiency, reduce waste, and deliver superior products. The two groups of programs for the three control processes (before, during and after production) relate to specialized textile software, integrated throwing laboratory hardware and production sensors, and MES / QMS systems.

The most comon software for apparel industry are Uster Quality Expert, BMSvision, and Barco Textiles in the first specialized group. In the second group of software are Pivot88 and Inspectoria Sight. We are present solution of Tekmon QMS, which allow manufacturers to conduct fabric tests, monitor production quality, and easily generate compliance reports.

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INDUSTRY 5.0 AND DIGITAL TRANSFORMATION FOR SUSTAINABLE TEXTILE AND MANUFACTURING SYSTEMS

Scientific paper
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ABSTRACT: *The rapid evolution of digital technologies has significantly transformed modern manufacturing systems, creating new opportunities for improving productivity, sustainability, and industrial resilience. In this context, Industry 5.0 has emerged as a new industrial paradigm that extends the technological achievements of Industry 4.0 by emphasizing human-centric manufacturing, sustainable production, and resilient industrial systems. Simultaneously, digital transformation has become a key enabler for integrating intelligent technologies into both textile and manufacturing industries, supporting resource-efficient production, process optimization, and environmentally responsible manufacturing practices. This paper presents a comprehensive review of the relationship between Industry 5.0, digital transformation, and sustainable textile and manufacturing systems. The study examines the fundamental principles of Industry 5.0 and discusses the role of enabling technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Big Data analytics, Cloud Computing, and Cyber-Physical Systems (CPS), in supporting intelligent manufacturing environments. Particular attention is devoted to the application of these technologies in textile manufacturing, where digitalization contributes to automated quality control, smart textile production, resource efficiency, digital product traceability, and circular production strategies. Based on the findings of the literature review, the authors propose a conceptual model of Industry 5.0-driven digital transformation that integrates three complementary dimensions: Digital Technologies, Human-Centred Manufacturing, and Sustainable Manufacturing. The proposed model illustrates how the interaction among these dimensions contributes to improved manufacturing performance through enhanced productivity, flexibility, product quality, environmental responsibility, and industrial resilience. Furthermore, the model demonstrates the importance of integrating technological innovation with human expertise and sustainability principles to support the future development of both textile and manufacturing systems. The proposed conceptual model may serve as a foundation for future research focused on intelligent manufacturing, smart textile production, Artificial*

Intelligence, Digital Twins, sustainable industrial development, and Industry 5.0 implementation strategies.

Keywords: *Industry 5.0; Digital transformation; Sustainable manufacturing; Textile industry; Smart manufacturing; Human-centred manufacturing.*

INDUSTRIJA 5.0 I DIGITALNA TRANSFORMACIJA ZA ODRŽIVE TEKSTILNE I PROIZVODNE SISTEME

APSTRAKT: *Brz razvoj digitalnih tehnologija značajno je transformisao savremene proizvodne sisteme, stvarajući nove mogućnosti za unapređenje produktivnosti, održivosti i otpornosti industrije. U tom kontekstu, Industrija 5.0 pojavljuje se kao nova industrijska paradigma koja proširuje tehnološka dostignuća Industrije 4.0 stavljajući poseban akcenat na proizvodnju usmerenu ka čoveku, održivu proizvodnju i otporne industrijske sisteme. Istovremeno, digitalna transformacija postala je ključni pokretač integracije inteligentnih tehnologija u tekstilnu industriju i proizvodne sisteme, omogućavajući efikasnije korišćenje resursa, optimizaciju procesa i ekološki odgovornu proizvodnju. U ovom radu dat je pregled odnosa između Industrije 5.0, digitalne transformacije i održivih tekstilnih i proizvodnih sistema. Analizirani su osnovni principi Industrije 5.0, kao i uloga ključnih digitalnih tehnologija, uključujući veštačku inteligenciju (Artificial Intelligence – AI), Internet stvari (Internet of Things – IoT), digitalne blizance (Digital Twins), analitiku velikih podataka (Big Data Analytics), računarstvo u oblaku (Cloud Computing) i sajber-fizičke sisteme (Cyber-Physical Systems – CPS), u razvoju inteligentnih proizvodnih okruženja. Posebna pažnja posvećena je primeni ovih tehnologija u tekstilnoj industriji, gde digitalizacija doprinosi automatizovanoj kontroli kvaliteta, pametnoj tekstilnoj proizvodnji, efikasnijem korišćenju resursa, digitalnoj sledljivosti proizvoda i primeni principa cirkularne proizvodnje. Na osnovu sprovedenog pregleda literature, autori predlažu konceptualni model digitalne transformacije zasnovan na Industriji 5.0, koji integriše tri komplementarne dimenzije: digitalne tehnologije, proizvodnju usmerenu ka čoveku i održivu proizvodnju. Predloženi model ilustruje kako međusobna interakcija ovih dimenzija doprinosi unapređenju proizvodnih performansi kroz povećanje produktivnosti, fleksibilnosti, kvaliteta proizvoda, zaštite životne sredine i otpornosti industrijskih sistema. Pored toga, model naglašava značaj integracije tehnoloških inovacija, ljudskog znanja i principa održivosti kao osnove budućeg razvoja tekstilne industrije i savremenih proizvodnih sistema. Predloženi konceptualni model može predstavljati osnovu za buduća istraživanja usmerena na inteligentnu proizvodnju, pametnu tekstilnu proizvodnju, veštačku inteligenciju, digitalne blizance, održivi industrijski razvoj i strategije implementacije Industrije 5.0.*

Ključne reči: *Industrija 5.0; Digitalna transformacija; Održiva proizvodnja; Tekstilna industrija; Pametna proizvodnja; Proizvodnja usmerena ka čoveku.*

1. INTRODUCTION

The manufacturing sector is currently undergoing a profound transformation driven by rapid technological advancements, increasing sustainability requirements, and the growing integration of digital technologies. Following the widespread implementation of Industry 4.0 concepts, the emergence of Industry 5.0 represents a new industrial paradigm that emphasizes human-centric production, resilience, and sustainability while maintaining the advantages of digital transformation and smart manufacturing technologies [3,10].

Digital transformation has become one of the primary drivers of competitiveness in modern manufacturing systems. Technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Big Data analytics, cloud computing, Digital Twins, and Cyber-Physical Systems (CPS) enable manufacturers to optimize production processes, improve product quality, increase flexibility, and reduce operational costs. These technologies simultaneously support data-driven decision-making and facilitate the transition toward more intelligent and sustainable manufacturing environments [4,6].

The textile industry is also experiencing significant changes resulting from digitalization, environmental regulations, and increasing customer demands for sustainable products. Traditional textile manufacturing is gradually evolving toward smart production systems characterized by automated processes, digital monitoring, resource-efficient production, and environmentally responsible manufacturing practices. Consequently, Industry 5.0 principles provide new opportunities for integrating advanced digital technologies with sustainable textile production while maintaining a strong focus on human creativity and industrial resilience [3,8].

Unlike Industry 4.0, which primarily focused on automation, connectivity, and productivity, Industry 5.0 places greater emphasis on collaboration between humans and intelligent technologies. Human expertise, creativity, and decision-making are considered essential components of future manufacturing systems, where digital technologies function as supporting tools rather than complete replacements for human operators. This transition reflects broader societal objectives related to sustainable development, circular economy principles, workforce well-being, and resilient industrial production [1,7]. Although numerous studies investigate Industry 5.0, digital transformation, or sustainable manufacturing independently, relatively few review papers systematically integrate these concepts within both textile and manufacturing systems. Establishing such an integrated perspective is increasingly important for supporting future industrial development and interdisciplinary research.

Therefore, the aim of this paper is to review the relationship between Industry 5.0, digital transformation, and sustainable manufacturing with particular emphasis on textile and manufacturing systems. The study analyses the key enabling technologies, current industrial applications, sustainability aspects, and future research directions while providing a comprehensive overview of the ongoing transition toward next-generation manufacturing.

2. FUNDAMENTALS OF INDUSTRY 5.0 AND DIGITAL TRANSFORMATION

Industry 5.0 represents the next stage in the evolution of industrial development, extending the technological achievements of Industry 4.0 by placing greater emphasis on human-centricity, sustainability, and resilience. While Industry 4.0 primarily focused on automation, connectivity, and intelligent production systems, Industry 5.0 promotes a balanced collaboration between advanced digital technologies and human expertise. This paradigm recognizes that future manufacturing should not only pursue productivity and efficiency but also create social, environmental, and economic value [1,3].

The concept of digital transformation forms the technological foundation of Industry 5.0. Digital transformation refers to the integration of digital technologies into manufacturing processes, organizational structures, and business models to improve operational performance, flexibility, and innovation. Rather than representing a single technological solution, digital transformation combines multiple enabling technologies, including Artificial Intelligence (AI), the Internet of Things (IoT), Big Data analytics, Cloud Computing, Cyber-Physical Systems (CPS), Digital Twins, robotics, and advanced data communication networks [4,6].

One of the distinguishing characteristics of Industry 5.0 is its human-centric approach. Instead of replacing human workers with automation, Industry 5.0 promotes collaboration between people and intelligent machines. Advanced robotics, collaborative robots (cobots), and artificial intelligence assist human operators by performing repetitive, hazardous, or computationally intensive tasks, allowing employees to focus on creativity, decision-making, problem-solving, and innovation. This collaborative environment contributes to higher productivity while simultaneously improving workplace safety and employee well-being [3,7].

Another key pillar of Industry 5.0 is sustainability. Modern manufacturing systems are increasingly expected to minimize environmental impacts through efficient resource utilization, energy optimization, waste reduction, circular economy principles, and environmentally responsible production strategies. Digital technologies provide valuable support for monitoring resource consumption, optimizing production parameters, predicting equipment failures, and reducing unnecessary material losses throughout the manufacturing lifecycle [3,8]. Resilience has also become a fundamental objective of Industry 5.0. Recent global disruptions, including supply chain instability and rapidly changing market conditions, have demonstrated the necessity of flexible manufacturing systems capable of adapting to unexpected challenges. Digital transformation enhances industrial resilience through real-time monitoring, predictive analytics, intelligent decision support, and adaptive manufacturing systems that enable rapid responses to changing production requirements [6,10].

Overall, Industry 5.0 should be viewed as a comprehensive industrial strategy that integrates digital technologies with human knowledge, sustainability principles, and resilient manufacturing systems. This integrated perspective provides the foundation for the future development of textile production and advanced manufacturing industries.

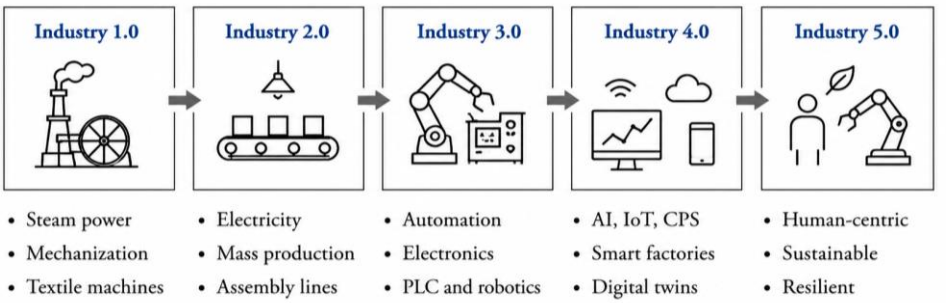

Figure 1: Evolution of industrial revolutions from Industry 1.0 to Industry 5.0

3. DIGITAL TRANSFORMATION IN TEXTILE AND MANUFACTURING SYSTEMS

Digital transformation has become one of the most significant driving forces behind the evolution of modern manufacturing systems. By integrating advanced digital technologies into industrial environments, manufacturers are able to improve operational efficiency, increase production flexibility, enhance product quality, and support sustainable manufacturing practices. Rather than representing the adoption of individual technologies, digital transformation involves the comprehensive integration of intelligent systems throughout the entire product lifecycle [4,6].

Within textile manufacturing, digital transformation enables substantial improvements in production planning, process monitoring, quality control, inventory management, and supply chain coordination. Smart sensors, automated inspection systems, and real-time data acquisition allow manufacturers to continuously monitor production parameters and rapidly identify process deviations. These technologies contribute to reduced material waste, improved resource utilization, and greater manufacturing flexibility while supporting increasingly customized textile production [3,8].

Artificial Intelligence (AI) has emerged as one of the most influential technologies supporting digital transformation. Machine learning algorithms enable predictive maintenance, quality prediction, defect detection, production scheduling, and intelligent decision-making based on large volumes of manufacturing data. AI-assisted optimization reduces production downtime, improves equipment utilization, and supports adaptive manufacturing strategies capable of responding to changing customer requirements [6,10].

Beyond conventional manufacturing, Artificial Intelligence is increasingly applied in textile production for automated fabric inspection, defect detection, colour consistency evaluation, production scheduling, and demand forecasting. Machine learning algorithms enable the identification of weaving and knitting defects, optimize dyeing parameters, and improve production planning, thereby reducing material waste and enhancing product quality. These intelligent systems support mass customization while simultaneously contributing to more sustainable textile manufacturing [6,8].

The Internet of Things (IoT) further strengthens digital manufacturing through interconnected sensors, machines, and production equipment capable of continuously exchanging operational information. Combined with cloud computing and Big Data analytics, IoT enables real-time monitoring of manufacturing systems, facilitating data-driven decision-making and improved process transparency. These technologies are particularly valuable for textile manufacturing, where continuous monitoring of temperature, humidity, machine performance, and production quality contributes to more stable and efficient manufacturing operations [4,5].

The Internet of Things also plays a significant role in modern textile manufacturing by enabling continuous monitoring of weaving, knitting, dyeing, and finishing operations. Smart sensors provide real-time information on machine conditions, temperature, humidity, energy consumption, and production quality, allowing manufacturers to rapidly respond to process deviations while improving resource efficiency and reducing production losses [4,5].

Digital Twins have also become increasingly important in Industry 5.0 environments. A Digital Twin represents a virtual replica of a physical manufacturing system that continuously receives operational data from the real production process. This technology enables virtual testing, process simulation, predictive maintenance, and optimization before implementing changes within industrial environments. Consequently, Digital Twins reduce development time, minimize production risks, and improve overall manufacturing performance [3,9].

In the textile industry, digital transformation supports intelligent weaving, knitting, dyeing, finishing, and garment manufacturing through automated production control, machine vision systems, RFID-based traceability, and AI-assisted quality inspection. These technologies improve production efficiency, reduce defects, optimize material utilization, and enable mass customization while supporting sustainable textile production [6,8].

Overall, digital transformation provides the technological foundation for Industry 5.0 by connecting intelligent digital technologies with human expertise and sustainable manufacturing principles. The successful integration of AI, IoT, Digital Twins, and advanced analytics enables manufacturing organizations to achieve higher productivity while simultaneously improving sustainability, resilience, and customer-oriented production.

Table 1: Digital technologies supporting Industry 5.0 in textile and manufacturing systems

Digital technology	Main application	Industrial benefit
Artificial Intelligence (AI)	Predictive maintenance and quality prediction	Improved productivity
Internet of Things (IoT)	Real-time monitoring	Process optimization
Digital Twins	Virtual simulation	Reduced development time
Big Data Analytics	Data-driven decision-making	Improved efficiency
Cloud Computing	Data storage and communication	Enhanced collaboration
Cyber-Physical Systems	Smart production integration	Flexible manufacturing

4. SUSTAINABLE TEXTILE AND MANUFACTURING SYSTEMS

Sustainability has become one of the defining principles of modern industrial development and represents a central pillar of Industry 5.0. Contemporary manufacturing systems are increasingly expected to achieve high levels of productivity while simultaneously reducing environmental impacts, improving resource efficiency, and ensuring long-term economic and social sustainability. Unlike previous industrial paradigms, Industry 5.0 places sustainability at the core of manufacturing strategies, promoting environmentally responsible production supported by advanced digital technologies [1,3].

Digital transformation also supports the development of smart textile manufacturing through digital textile printing, automated cutting systems, intelligent material handling, and real-time production traceability. These technologies facilitate customized production, improve process flexibility, and contribute to more efficient utilization of textile materials while supporting circular production strategies. Furthermore, digital product passports and traceability systems are expected to play an increasingly important role in textile recycling and sustainable supply chain management [2,8].

Within the textile industry, sustainability has become particularly important due to high energy consumption, intensive water usage, chemical processing, and significant waste generation throughout the production lifecycle. Digital transformation enables textile manufacturers to optimize resource utilization, monitor environmental performance, improve process efficiency, and reduce emissions through intelligent production management. Technologies such as AI, IoT, and Digital Twins contribute to more efficient control of textile manufacturing processes while supporting sustainable production practices [6,8].

Energy efficiency represents another major objective of sustainable manufacturing systems. Real-time monitoring, predictive analytics, and intelligent process optimization enable manufacturers to reduce unnecessary energy consumption while maintaining production quality and operational stability. Smart manufacturing technologies further contribute to minimizing equipment downtime, optimizing machine utilization, and extending equipment lifetime through predictive maintenance strategies [4,5].

Resource efficiency and circular production principles have also become fundamental components of sustainable manufacturing. Industry 5.0 encourages manufacturers to optimize raw material utilization, reduce production waste, improve recycling practices, and implement closed-loop manufacturing systems whenever possible. Digital technologies facilitate these objectives by enabling continuous monitoring of material flows, production efficiency, and environmental performance throughout the product lifecycle [2,3].

The transition toward circular textile manufacturing additionally requires the integration of digital technologies capable of tracking material flows throughout the entire product lifecycle. Advanced information systems support textile collection, sorting, recycling, and remanufacturing processes, thereby improving material recovery and enabling more efficient implementation of circular economy principles within the textile sector [1,2].

Furthermore, sustainability within Industry 5.0 extends beyond environmental considerations by incorporating social responsibility and human well-being. Human-centred manufacturing emphasizes safe working environments, employee development, collaborative robotics, and improved interaction between workers and intelligent manufacturing systems. Consequently, sustainable manufacturing should be understood as the balanced integration of technological innovation, environmental responsibility, economic competitiveness, and human welfare [1,7].

Overall, sustainable textile and manufacturing systems demonstrate that digital transformation and Industry 5.0 are mutually reinforcing concepts. Digital technologies provide the technological capabilities necessary for sustainable production, while Industry 5.0 establishes the strategic vision for integrating technological innovation with environmental stewardship and human-centred industrial development.

Table 2: Sustainability dimensions supported by Industry 5.0 technologies

Sustainability dimension	Industry 5.0 contribution	Example
Environmental	Resource efficiency	Reduced energy and material consumption
Economic	Intelligent process optimization	Lower production costs
Social	Human-centred manufacturing	Improved workplace safety
Technological	Digital transformation	AI, IoT and Digital Twins
Circular	Closed-loop production	Recycling and material recovery

5. CONCEPTUAL MODEL FOR INDUSTRY 5.0 - DRIVEN DIGITAL TRANSFORMATION

The literature reviewed throughout this study demonstrates that Industry 5.0 extends beyond the technological focus of Industry 4.0 by integrating digital innovation with sustainability, resilience, and human-centred manufacturing. Although numerous studies investigate individual enabling technologies or sustainability strategies, relatively limited attention has been devoted to presenting a unified conceptual model that illustrates how these elements collectively support the digital transformation of textile and manufacturing systems [1,3].

Based on the reviewed literature, a conceptual model is proposed to illustrate the relationship between Industry 5.0 principles, digital transformation technologies, and sustainable manufacturing objectives. Rather than representing a sequential implementation procedure, the proposed model emphasizes the interaction between technological innovation, organizational transformation, and sustainability-oriented manufacturing strategies.

At the core of the model is Industry 5.0, which provides the strategic vision for future manufacturing systems. Three complementary dimensions support this vision.

The first dimension, Digital Technologies, includes Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Big Data Analytics, Cloud Computing, and Cyber-Physical Systems. These technologies provide real-time data acquisition, intelligent decision-making, process automation, and predictive manufacturing capabilities [5,6].
The second dimension, Human-Centred Manufacturing, emphasizes collaboration between human expertise and intelligent technologies. Advanced automation and collaborative robots support workers by improving productivity, occupational safety, knowledge sharing, and innovation while maintaining human decision-making as a central component of manufacturing systems [3,7].
The third dimension, Sustainable Manufacturing, focuses on resource efficiency, energy optimization, circular production, waste reduction, environmental responsibility, and resilient industrial development. Digital technologies enable continuous monitoring and optimization of manufacturing processes, thereby supporting more sustainable and competitive production systems [2,8].
The interaction among these three dimensions leads to improved manufacturing performance through higher productivity, increased flexibility, enhanced product quality, reduced environmental impacts, and greater industrial resilience. Consequently, the proposed conceptual model demonstrates that successful digital transformation requires the simultaneous integration of technological innovation, human involvement, and sustainability principles rather than focusing exclusively on technological advancement.

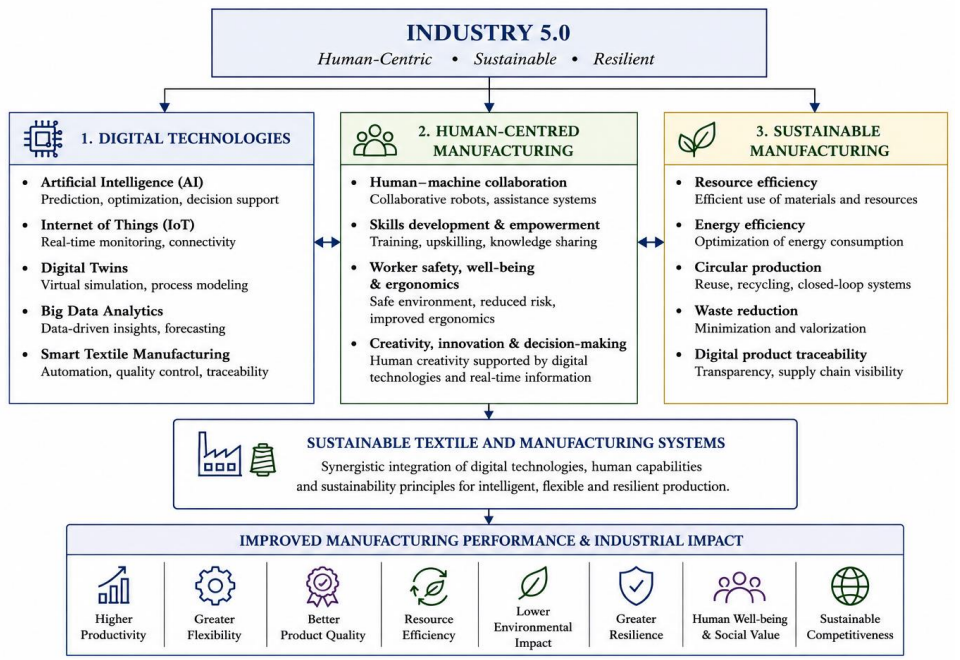

Figure 2: Conceptual model of Industry 5.0-driven digital transformation for sustainable textile and manufacturing systems

6. FUTURE RESEARCH DIRECTIONS

The transition toward Industry 5.0 is expected to accelerate the integration of advanced digital technologies with sustainable and human-centred manufacturing systems. Future research should focus on developing comprehensive methodologies capable of simultaneously integrating Artificial Intelligence (AI), Digital Twins, the Internet of Things (IoT), Big Data analytics, and Cyber-Physical Systems into unified manufacturing environments. Such integrated approaches may significantly improve manufacturing efficiency, flexibility, and sustainability while supporting more resilient industrial production systems [3,6].

One promising research direction involves the application of Artificial Intelligence for autonomous decision-making, predictive maintenance, intelligent quality control, and adaptive manufacturing. Combining AI with real-time production data may enable self-optimizing manufacturing systems capable of continuously improving production performance while reducing operational costs and environmental impacts [4,10].

Another important area concerns the wider implementation of Digital Twins throughout the entire product lifecycle. Future Digital Twin platforms are expected to integrate simulation, process monitoring, predictive analytics, and sustainability assessment within a single digital environment. Such integration would enable manufacturers to evaluate production scenarios before implementation, reduce material waste, improve equipment utilization, and support more sustainable industrial operations [9].

Future investigations should also explore the integration of Industry 5.0 technologies within smart textile manufacturing, including intelligent textile production systems, digital textile printing, automated fabric inspection, wearable technologies, digital product passports, and AI-assisted textile recycling. These emerging technologies may significantly improve sustainability, product traceability, and circular textile manufacturing while supporting more resilient textile supply chains [2,8].

Future research should additionally investigate human-machine collaboration in increasingly digital manufacturing environments. Developing collaborative production systems that combine advanced automation with human creativity, expertise, and decision-making will remain one of the defining characteristics of Industry 5.0. These systems should prioritize worker well-being, occupational safety, continuous learning, and technological adaptability while maintaining high manufacturing performance [1,7].

Overall, future developments should concentrate on establishing manufacturing ecosystems in which digital transformation, sustainability, resilience, and human-centred production operate as complementary components of a unified industrial strategy capable of supporting long-term technological and societal progress.

7. CONCLUSION

Industry 5.0 represents a significant evolution of modern manufacturing by extending the technological capabilities introduced in Industry 4.0 toward a more human-centred, sustainable, and resilient industrial paradigm. As demonstrated throughout this review,

digital transformation has become the primary enabler of this transition by integrating advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twins, Big Data analytics, Cloud Computing, and Cyber-Physical Systems into manufacturing environments. These technologies contribute not only to improved operational efficiency but also to enhanced sustainability, flexibility, and industrial competitiveness [3,6].

The analysis presented in this paper demonstrates that digital transformation and Industry 5.0 provide significant opportunities for both advanced manufacturing and textile production by supporting intelligent process optimization, automated quality control, resource-efficient manufacturing, and sustainable industrial development. These concepts operate as complementary strategies that support sustainable textile and manufacturing systems. The integration of digital technologies enables manufacturers to improve productivity while simultaneously reducing energy consumption, material waste, and environmental impacts [4,8].

As the principal contribution of this study, a conceptual model of Industry 5.0-driven digital transformation was proposed to illustrate the interaction between three fundamental dimensions: Digital Technologies, Human-Centred Manufacturing, and Sustainable Manufacturing. The proposed model provides a systematic perspective for understanding how these complementary dimensions collectively contribute to improved manufacturing performance. Unlike conventional technology-oriented approaches, the model emphasizes the balanced integration of technological innovation, human expertise, and sustainability principles as the foundation for future industrial development.

The findings presented in this review may serve as a conceptual basis for future investigations focused on intelligent manufacturing, Digital Twins, Artificial Intelligence, smart textile production, and sustainable industrial systems. Furthermore, the proposed model may support researchers and industrial practitioners in developing integrated manufacturing strategies capable of addressing future technological, environmental, and societal challenges associated with Industry 5.0.

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IMMERSIVE TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE IN THE TRANSFORMATION OF FASHION SALES

Professional paper
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ABSTRACT: *The digital transformation of the fashion industry has led to the adoption of augmented reality, virtual reality, and artificial intelligence as strategic tools for improving sales, customer experience, and business sustainability. This paper presents an integrative review of contemporary research and industry practice, analysing the impact of immersive technologies on consumer behaviour and business performance in the fashion industry. Drawing on the stimulus-organism-response paradigm, technology acceptance theories, and the concept of dynamic capabilities, it develops a conceptual framework in which these technologies influence consumer decisions by increasing the sense of presence and perceived value and reducing purchase uncertainty. The results indicate that they can raise conversion rates and potentially reduce product returns, while digital twins and virtual sampling create opportunities for more sustainable processes. The paper examines implementation challenges in small and medium-sized enterprises and proposes a framework for gradual, resource-efficient digital transformation.*

Keywords: *augmented reality, virtual reality, artificial intelligence, fashion industry, sustainability, fashion metaverse, digital assets (NFTs).*

IMERZIVNE TEHNOLOGIJE I VEŠTAČKA INTELIGENCIJA U TRANSFORMACIJI MODNE PRODAJE

APSTRAKT: *Digitalna transformacija modne industrije dovela je do primene proširene stvarnosti, virtuelne stvarnosti i veštačke inteligencije kao strateških alata za unapređenje prodaje, korisničkog iskustva i održivosti poslovanja. Rad predstavlja integrativni pregled savremenih istraživanja i industrijske prakse sa ciljem analize uticaja imerzivnih tehnologija na ponašanje potrošača i poslovne performanse. Polazeći od paradigme stimulus–organizam–odgovor, teorija prihvatanja tehnologije i koncepta dinamičkih sposobnosti, rad razvija konceptualni okvir prema kojem ove tehnologije utiču na odluke potrošača kroz povećanje osećaja prisutnosti i percipirane vrednosti i smanjenje neizvesnosti pri kupovini. Rezultati ukazuju da one mogu doprineti povećanju stope*

konverzije i potencijalnom smanjenju povraćaja proizvoda, dok digitalni blizanci i virtuelno uzorkovanje otvaraju mogućnosti za održivije procese. Rad razmatra izazove implementacije u malim i srednjim preduzećima i predlaže okvir za postepenu i resursno efikasnu digitalnu transformaciju.

***Ključne reči**: proširena stvarnost, virtuelna stvarnost, veštačka inteligencija, modna industrija, održivost, modni metaverzum, digitalna dobra (NFT).*

1. INTRODUCTION

The fashion industry has undergone intensive digital transformation, driven by shifting consumer behavior and the accelerated adoption of digital technologies [1]. Augmented Reality (AR), Virtual Reality (VR), and Artificial Intelligence (AI) have thus evolved from experimental marketing tools into strategic instruments for sales performance and customer experience [2].

The primary challenge addressed by these technologies is the *trust gap* in online fashion retail: consumers cannot physically assess a product's appearance, size, and fit before purchase, which raises perceived risk, lowers purchase intention [3,4], and drives high return rates.

From a strategic management perspective, this study examines how AR, VR, and AI contribute to fashion sales, evaluates the evidence for their effectiveness, and proposes a framework for gradual implementation, with particular attention to small and medium-sized enterprises (SMEs), underrepresented in the literature relative to luxury brands.

2. RESEARCH METHODOLOGY AND THEORETICAL FRAMEWORK

This study applies an integrative literature review, an approach suited to emerging fields with diverse and rapidly evolving evidence [5]. Unlike PRISMA-based systematic reviews, it allows the inclusion of both peer-reviewed publications and industry reports. Publications were identified through Scopus and Web of Science searches on AR, VR, VTO, the metaverse, digital twins, and digital assets in fashion retail, covering studies from 2016-2026 and excluding purely technical work without business or consumer outcomes. Industry reports were treated as a separate evidence category given potential commercial bias. Three cases — Gucci, Burberry, and Louis Vuitton — were purposively selected and assessed by technology, strategic objective, reported outcome, and transferability [6].

The theoretical foundation integrates four complementary perspectives [7-13]. The Stimulus-Organism-Response (S-O-R) paradigm explains how AR and VR act as external stimuli shaping consumers' cognitive and emotional responses, and thus purchase intention, with interactivity, vividness, and telepresence increasing perceived value [3,7,8]. TAM and UTAUT explain the determinants of adoption, where experiential and social benefits often outweigh purely economic considerations [9-11]. Presence Theory highlights the value of immersion alongside limitations such as simulator sickness [12]. The Dynamic Capabilities perspective holds that transformation depends not only on technology investment but on

the ability to sense opportunities and integrate new technologies into existing processes [13].

Figure 1 integrates these strands: AR, VR and digital-twin stimuli act on purchase and firm outcomes through telepresence, perceived value and reduced uncertainty, while AI functions as an enabling layer and firm-level capabilities moderate the outcome.

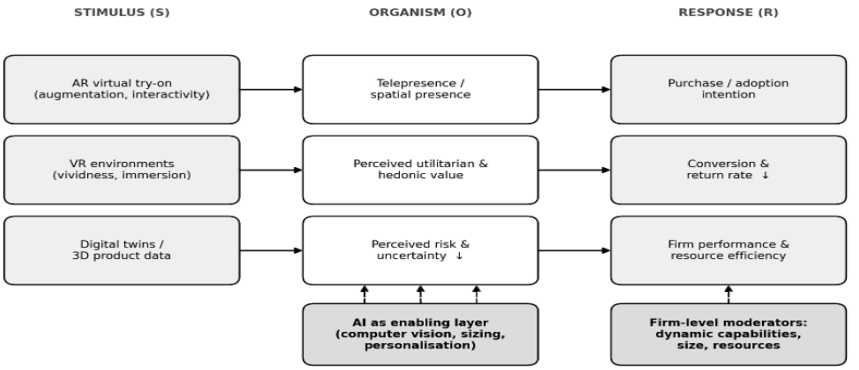

Figure 1: Conceptual model of immersive technology effects in fashion retail [7,8].

3. IMMERSIVE TECHNOLOGIES AS TOOLS FOR SALES DEVELOPMENT

AR is the most mature and widely adopted of the three, largely because it runs on devices consumers already own. Its most prominent application, Virtual Try-On (VTO), lets consumers evaluate clothing, footwear, and accessories in real time; empirical studies consistently show that AR enhances presence, perceived usefulness, and satisfaction, positively influencing purchase intention [3,8,11].

Industry reports also suggest that AR may reduce product return rates. These findings should be interpreted with caution, as they frequently originate from technology providers with a commercial interest in promoting their solutions [14].

VR, by contrast, creates fully immersive environments enabling new retail models — virtual showrooms, digital fashion shows, and fashion metaverses — extending brand reach beyond physical presence. Research nonetheless points to a gap between consumer and corporate expectations: consumers see the metaverse as a space for self-expression, companies primarily as a new business channel [15].

AI functions as the technological foundation integrating these solutions: computer vision enables more realistic AR visualization, while analysis of purchasing and return data supports personalized product and sizing recommendations. Its greatest value lies not in standalone use but in enhancing the accuracy of the other technologies.

4. EMERGING MODELS OF FASHION RETAILING

The development of AR, VR, and AI has produced new retailing models that differ in complexity, required investment, and the strength of the evidence behind them (Table 1).

VTO is the most mature, directly addressing consumers' inability to interact physically with products before purchase [3,8]. Virtual showrooms and digital fashion shows mainly enhance brand visibility and best suit large brands with established identities [15]. AI-driven recommendation offers sales potential but depends on high-quality consumer data, often a constraint for SMEs [2]. Digital twins shorten development cycles and improve traceability, gaining importance under EU initiatives such as the Digital Product Passport [16,17,18]. Digital goods and NFTs remain the most experimental segment: authenticity and exclusivity are established value drivers, but market developments since the initial growth phase warrant caution [19,20].

Table 1: *Comparative assessment of immersive sales models in fashion retail (author's assessment, synthesised from the reviewed literature).*

Model	Investment	Complexity	Effect on sales	Sustainability effect	SME suitability	Maturity
Virtual tryon (VTO)	Med.-high (3D assets/SKU)	Medium	Direct: conv. ↑, returns ↓	Indirect: fewer returns	High	Mature
Virtual showrooms / shows	High	High	Indirect: reach, awareness	Lower travel footprint	Low	Emerging
AI personalisation & sizing	Low–med. (SaaS)	Med. (data-dep.)	Direct: AOV ↑, returns ↓	Indirect	Medium	Mature
Digital twins / 3D sampl.	High upfront, falling/unit	High	Indirect: lead time ↓, cost ↓	Direct: fewer samples	Low–medium	Consoli-dating
Digital goods / NFTs	Medium	High (reg., technical)	Speculative, post-2022	Ambiguous	Low	Contested
Connected stores	Low–medium	Low-medium	Direct: footfall, basket	Indirect: logistics	High	Mature

5. BUSINESS AND ENVIRONMENTAL EFFECTS

Immersive technologies can improve business performance by raising conversion rates, enhancing customer experience, and reducing purchase uncertainty. Empirical research confirms AR's positive effects on consumer attitudes and purchase intention, though evidence for its effectiveness in reducing return rates remains limited and not independently validated [3,8,11].

Digital twins and 3D modelling improve product development by reducing physical prototyping and shortening cycles [16], though the benefits are not distributed equally across the value chain: a substantial share is often captured by the technology providers themselves.

From a sustainability perspective, these technologies can reduce material consumption, waste, and unnecessary transport while improving traceability [17,18]. Sustainability is not automatic, however: the footprint of the digital infrastructure itself — energy, computing, data storage — must also be counted [16], and robust assessment requires life cycle assessment (LCA).

6. COMPARATIVE ANALYSIS AND IMPLEMENTATION OPPORTUNITIES

Through the *Gucci Garden Experience* and *Gucci Town* initiatives on Roblox, Gucci used digital environments primarily to build brand awareness among younger consumers. The virtual Dionysus handbag's high resale price was an isolated case, not evidence of a sustainable model [21]; the value lay instead in new forms of engagement and expanded digital presence [15].

Burberry's social retail concept with Tencent integrated a physical store with digital content and WeChat into a seamless omnichannel experience [22], demonstrating the potential of physical-digital integration, though transferability is limited by China's specific digital ecosystem and the absence of verified performance data.

Louis Vuitton illustrates VR used to extend global access to fashion shows, though its success depends on the brand's existing market position, which limits applicability to smaller companies.

Technology selection should therefore follow, not precede, strategic objectives, since the same technology can serve purposes ranging from brand awareness to new sales channels. Evidence quality tends to decline as initiatives grow more sophisticated, while applicability declines as resource requirements rise.

For SMEs, the principal barriers are the cost of developing 3D product models, skills shortages, technical constraints, and data protection requirements, making organizational capabilities and resource availability critical determinants of successful transformation [18].

These findings are particularly relevant to the Western Balkan textile industry, predominantly based on OEM and CMT production. Manufacturers typically lack direct customer relationships, behavioral data, and proprietary sales channels, so the feasible direction is digital sampling, digital twins, and traceability, while own-brand companies are better positioned for connected retail.

7. IMPLEMENTATION FRAMEWORK AND RISK MANAGEMENT

Successful implementation requires a gradual approach aligning business objectives with technological opportunities and organizational capabilities. The first stage assesses the current state — return and conversion rates, product portfolio, data availability, and employee competencies — to establish whether the core challenge is product fit or product discovery. A pilot on a limited product range then guides decisions on internal capability-building or external collaboration.

Full implementation requires integrating digital solutions with existing e-commerce, inventory, and enterprise systems, alongside investment in employees' digital competencies, since technology alone is no advantage without the capability to use it [13].

Outcomes should be assessed against defined KPIs: return and conversion rates, average order value, engagement, and model maintenance cost.
Adoption also requires risk management: VTO applications process biometric data, making privacy a key determinant of acceptance [23], alongside algorithmic bias, digital exclusion of consumers with older devices, and data-protection duties. Implementation is therefore iterative: pilot, evaluate, expand where value is demonstrated.

8. CONCLUSION

AR, VR, and AI are becoming increasingly important components of sales development strategy in the fashion industry, their principal value lying in reduced uncertainty and enhanced customer experience. The evidence confirms AR's positive influence on engagement and purchase intention, though its effectiveness in reducing returns and contributing to sustainability remains insufficiently supported. The theoretical contribution lies in linking consumer behavior research with the digital transformation literature through the S-O-R paradigm and dynamic capabilities.
From a managerial perspective, strategic objectives should determine technology selection, and phased pilot-based implementation is more rational than large upfront investment without prior validation. For SMEs operating under OEM/CMT models, digital sampling, digital twins, and traceability systems remain the most promising solutions.
Limitations arise from the integrative nature of the review, the small number of luxury-brand cases, and the absence of primary data. Future research should independently assess effects on return rates, evaluate environmental impact through life-cycle methodologies, and empirically test applicability in the Western Balkan textile industry.

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SESSION IV
ECOLOGY AND SUSTAINABLE DEVELOPMENT

TEXTILE WASTE–DERIVED FABRIC FORMWORK FOR CONCRETE AND MORTAR: ENABLING GEOMETRIC FLEXIBILITY

Scientific paper
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ABSTRACT: *Fashion and textile industry generate substantial volume of waste, during the production phase, as well as in the consuming phase. This waste is disposed in the landfills or incinerated significantly affecting the environment. At the same time, construction industry faces its own demands to reduce carbon dioxide emissions, to reconsider, among other things, the approach to the conventional formwork systems, being resource intensive and disposed after the use. This paper explores the feasibility of the usage of the textile waste in the form of the flexible formwork, for the casting of the elements made of concrete and mortar. The properties of textile, such as deformability and tensile capacity are used to make the formwork of non-standardized geometry while minimizing the material consumption. This paper shows performances, adaptability and the consequences of the application of textile waste fabric formwork in non-structural architectural products. The results obtained show that the recycled textile waste can be used as efficient and low-cost alternative to traditional formwork, while providing flexible geometrical shapes of the products and the reducing the environmental impact. This paper can be seen as a contribution to the development of the circular economy strategy in the cement-based construction industry, while introducing the new sustainable practices in architectural engineering.*

Keywords: *textile waste, material reuse, fabric formwork, concrete and mortar, sustainability, geometric flexibility.*

OPLATA ZA BETONE I MALTERE OD TEKSTILNOG OTPADA: OMOGUĆAVANJE FLEKSIBILNIH GEOMETRIJA

APSTRAKT: *Modna i tekstilna industrija generišu značajnu količinu otpada, kako tokom proizvodnje, tako i tokom upotrebe. Ovaj otpad se odlaže na deponije ili spaljuje, što*

značajno utiče na životnu sredinu. Istovremeno, građevinska industrija se suočava sa zahtevima za smanjenje emisije ugljen-dioksida, i za preispitivanjem, između ostalog, korišćenja konvencionalnih sistema oplate, koji intenzivno koriste resurse i postaju otpad nakon upotrebe.Ovaj rad istražuje mogučnost upotrebe tekstilnog otpada u obliku fleksibilne oplate za livenje elemenata od betona i maltera. Svojstva tekstila, kao što su deformabilnost i zatezna nominalna čvrstoća, koriste se za izradu oplate nestandardizovane geometrije uz minimiziranje potrošnje materijala. Ovaj rad prikazuje svojstva, prilagodljivost i uticaje primene oplate od tekstilnog otpada u nekonstruktivnim arhitektonskim proizvodima. Dobijeni rezultati pokazuju da se reciklirani tekstilni otpad može koristiti kao efikasna i jeftina alternativa tradicionalnoj oplati, uz istovremeno obezbeđivanje fleksibilnih geometrijskih oblika proizvoda i smanjenje uticaja na životnu sredinu. Ovaj rad se može posmatrati kao doprinos razvoju strategije cirkularne ekonomije u industriji proizvodnje betona, uz uvođenje novih održivih praksi u arhitektonsko inženjerstvo.

Ključne reči: *tekstilni otpad, reciklaža materijala, tekstilna oplata, malter i beton, održivost, fleksibilne geometrija.*

1. INTRODUCTION

The construction industry is one of the biggest causes of change and often degradation of the environment. Global urbanization became rapid, contributing to the construction of the necessary new infrastructural facilities, along with simultaneous removal and adaptation of the those that exist, while consuming large amounts of natural resources and leaving a significant amount of construction waste. According to some sources, the construction industry is responsible for almost a third of all waste in the world [1][2][3]. The largest portion of the generated waste comes from the demolition of existing structures, and the rest (approximately 10%) is generated during the construction of new ones [4].

Another significant part of municipal waste is textile waste, which in most cases is incinerated or disposed of in landfills. During recent years, researches paid a lot of attention to the new methods of textile recycling [5][6][7]. The focus is shifted from basic mechanical recycling to more advance chemical [8] and recycling using biodegradation [9]. Still, many recycling procedures used sometimes harm the environment more than the waste itself [10]. Despite all efforts, large increase of the textile production volume affects the environment, so the recycling of used textiles remains an open challenge [11].

The majority of methods used for textile recycling rely on conversion of the fabric into fibers that are then reused [12]. New methods for automated separation of textiles according to the fiber type and origin are rapidly being developed [13]. Although a lot of work and energy is invested in the production of textiles, a limited number of studies deal with ways to recover the invested energy and material in the most efficient way [14].

The application of textiles in construction and concrete constructions is in two ways: as specially produced fibers or meshes made of glass, polyethylene, or carbon that are embedded in concrete and mortar as reinforcement, in order to increase the tensile strength

of the base material [15][16], or it is used as a textile flexible formwork for pouring concrete and mortar in a special deformable mold, in order to obtain unusual curved shapes that cannot be formed using the usual wooden and metal formwork [17].

2. FABRIC FORMWORK FOR CONCRETE

The first industrial applications and patents for the use of textiles as formwork for concrete date back to the 19th century [18], and historical traces date back to the beginnings of the use of concrete in the Roman era [19]; however, the textile formwork usage wasn't significant in the concrete production industry and in concrete structures' construction [20]. Textile formwork is fundamentally different from conventional wooden or metal formwork. Conventional formwork made by usage of the rigid flat wooden or metal sheets are used to produce rectangular flat concrete forms. Achieving curved shapes of the product made of concrete using this type of formwork is more expensive and technically demanding. On the other side, soft, stretchable and easily deformable textile materials provide free and curved forms much more easily and affordably. Free and diverse form of the elements is enabled using tailoring the textile fabric and the hydrostatic pressure of the fresh concrete mixture. This free approach to the formation of the geometry of concrete elements is not easy to reconcile with the completely deterministic way in which concrete structures are calculated and constructed.

On the other hand, the freedom and flexibility that textile formwork along with the variety of concrete surface textures that faithfully replicate textile formwork, have attracted the attention of numerous artists, architects, architectural and structural engineers. Work of many authors (Mark West, at the University of Manitoba, C.A.S.T projects, Anne-Mette Manelius at the Royal Danish Academy of Fine Arts, John J. Orr and Will Hawkins, at the University of Bath, etc.), have explored the numerous possibilities offered by this type of formwork in the fields of art, architecture, construction, optimization, topology, etc. [21][22]. According to the typology and the nature of the load, formwork can be divided into two categories [22]: formwork that changes shape when filled with concrete (filled molds), and formwork that preserves its shape (surface molds).

According to the textile recycling procedures, the most common methods of textile recycling are mechanical (fiber shredding), chemical and biochemical (chemical decomposition of fibers), energy production (incinerating) and re-usage, upcycling and creative reusing (reuse of textiles or parts in a different way) [24][25][26].

The use of recycled textile waste in the form of fibers for reinforcing concrete and cement mortars creates some problems due to the accumulation of dirt and their uncontrolled distribution on the composite material, and is not suitable for the production of textile formwork. The best method for the production of textile formwork from used or waste textile is the reuse method where the textile waste, after being sorted, is connected into a whole. For the production of formwork that changes its shape, parts of textile waste can be sewn, while for the production of pre-formed textile formwork that preserves the given shape, parts of textile waste can be glued. When the textile parts are glued, the durability and load-bearing capacity of such textile formwork depends on the load-bearing capacity

of the joints. This paper will present the testing of textile waste joints for the production of preformed formwork made from textile waste glued using a polymer-cement binder.

Figure 1: Research into various applications of textile formwork (Mark West (CAST), according to [22])

3. EXPERIMENTAL RESULTS AND DISCUSSION

The objective of this experiment was to test whether it is possible to use cement-based and polymer-based binders to create a bond between two pieces of textile. Cement is the basic binder in cement mortars and concretes. When mixed with water, it begins to harden and forms cement paste and cement matrix, which includes fillers, most often stone aggregate, and forms a hardened material known as concrete. In reinforced concrete, cement paste is sufficient to transfer tensile and compressive forces from one steel bar to the next one.
Waste material from the production of T-shirts, made by of organic cotton, was selected for the experiment. In contrast to cement mortar and concrete, this material is very elastic in both directions, so one of the intentions was to test to what extent the stiffness of the cement binder will affect the elasticity of the composite material.
Special attention was paid to the selection of the cement binder used for the connection and continuation of the textile pieces. As a cement binder, different proportions of the polymer-cement materials were selected for further testing, due to their greater elasticity and adhesion. The final choice was the polymer-cement mixture obtained from a manufacturer consisting of a liquid component based on acrylate latex and a powder component based on cement of quality CEM I 42.5. The polymer-cement material was tested on prismatic samples 40 mm × 40 mm × 160 mm. The properties of the polymer-cement material used as a binder for pieces of waste textiles are given in Table 1.

Table 1: Properties of the selected polymer-cement material

Property	MPa
Bending strength, after 7 days	7,0
Bending strength, after 28 days	9,0
Compressive strength, after 7 days	30,0
Compressive strength, after 28 days	41,0
Adhesion for concrete surface	2,4

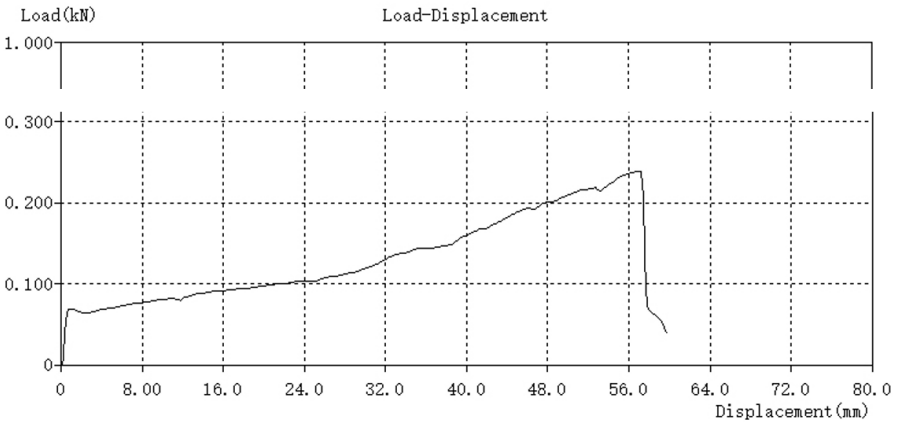
In order test the effect of the polymer-cement coating on properties of waste textiles, as well as the capability of gluing textile pieces, tests were conducted on samples. The tests were carried out on a textile tearing machine on textile samples measuring 350 mm × 50 mm, with a thickness of d = 0.5 mm. The tensile strength of the textile was tested on control samples made of untreated textiles and those made of textiles coated with polymer-cement material. In order to test the overlap of textile pieces, samples were coated and overlapped using the layer of polymer-cement material. The overlap of two textile pieces was in the middle of the tested sample. Three different length of the overlap were tested: 25 mm, 37.5 mm and 50 mm, corresponding to the 50 d, 75 d and 100 d, where d is the thickness of the textile. The test results are shown in Table 2.

Table 2: Tensile forces and deformations on samples of whole and joined textile parts

Type of sample	Average Force (N)	Average dilatation (mm)
Referent uncut textile	182	148,0
P-C coated uncut textile	248	58,4
Double P-C coated uncut textile	576	80,6
P-C coated cut textile, overlap 25 mm	240	55,9
P-C coated cut textile, overlap 37,5 mm	256	47,8
P-C coated cut textile, overlap 50 mm	272	52,3

The test results showed that polymer-cement material coating of the textile increases the total tensile force during which the sample breaks (by 36%), while at the same time it significantly reduces the elongation of the composite sample (by 60%). This is expected, since the polymer-cement material, during the hardening process, fills the gaps between the threads of the knitting, thus preventing large elongations.

The test results justified the assumption that it is possible to provide the continuation of the waste pieces of textiles using polymer-cement material. The overlap length of 25 mm practically enables the same tearing force (97% compared to the unbroken pattern) to be achieved as with an unbroken textile. Longer overlaps, 37.5 mm and 50 mm, increase the tear force by 3% and 10%, respectively, while reducing sample elongation. A small increase in tearing force is probably due to a thicker layer of polymer-cement material around and at the place of the overlap. Load-displacement diagram (Figure 2) shows



increased stiffness of a composite material at the beginning, and further decrease in elastic modulus due to formation of cracks.

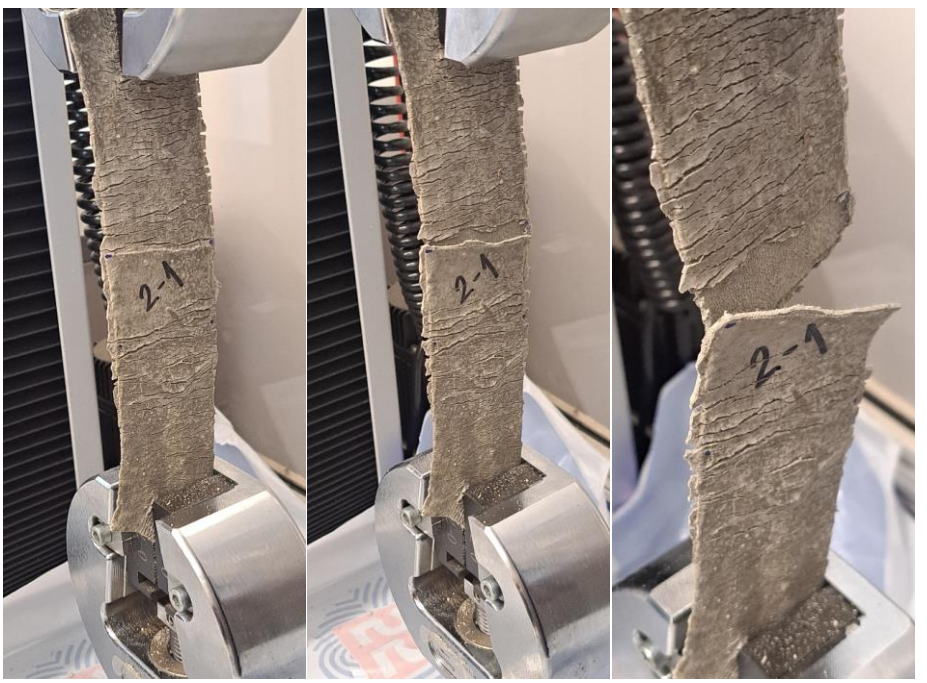


Figure 2: Tension test phases of overlapped joint (25 mm)

The distribution of cracks on the samples shows that they are formed evenly, which means that the waste textile enables uniform deformation of the sample. This is not the case in

plain polymer-cement materials, where the first crack propagates and leads to breakage (Figure 3). On the other hand, the total elongation reduction is the result of a longer length of the overlap, where the cracks do not appear, even when the overlap delaminates.

4. CONCLUSION

The construction industry has a major impact on the environment, both due to the significant use of resources and energy, and due to the large amount of waste it generates. At the same time, it also has great potential for the application and recycling of waste generated in other industries. The textile and fashion industries are major producers of used materials that end up as waste. Reusing this waste is a modern challenge.

Textile formwork has been present in construction for a long time. Textile formwork offers great opportunities for faster, more flexible and more affordable construction. Research has shown that it is possible to form textile formwork from parts of waste textiles in a simple way, by bonding them with a cement-polymer binder. Such formwork can be pre-formed into the required dimensions or shapes, and more importantly, simply continued on site. Preformed formwork from textile waste can be finished as a final texture, and thus become part of the structure.

The test showed that coating of the textile using polymer-cement material increases the tensile strength of the composite, while at the same time significantly reduce the elongation. The test also showed that pieces of the textile can be glued using the selected polymer-cement material simply by overlapping. It was shown that the overlap length of 25 mm practically achieve the same tearing force (97%) in the sample with overlapped pieces as in the sample made by continuous textile pieces (100%). Overlaps of 37.5 mm and 50 mm increase the tearing force by 3% and 10% respectively, with a decrease in elongation. The small increase in tearing force originates from the thicker layer of polymer-cement material at the overlap, while the decrease in elongation is the result of the longer overlap length, where cracks do not occur.

In order to fully realize the potential of preformed formwork from waste textiles, further research is necessary, not only to determine the characteristics of the formwork itself, but also to expand the field and methods of its application. We are facing the challenges of testing the applicability and durability of such materials. In this process, engineers from all professions (architects, technologists, civil engineers, mechanical engineers) must work closely and collaborate.

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BIOMASS WASTE–DERIVED COMPOSITE AEROGEL MATERIALS FOR SUSTAINABLE PASSIVE RADIATIVE COOLING

Scientific paper
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ABSTRACT: *Passive radiative daytime cooling (PRDC) materials attract attention as today's innovative materials by mitigating global warming and lowering energy consumption without any energy input. However, the petroleum-based non-biodegradable sources of the polymers creates a negative burden on the environment. In this study, a sustainable and efficient PDRC composite aerogel was developed through freeze-drying using silk fibroin (SF) from waste silkworm cocoons, cellulose nanofiber (CNF) as the matrix components and aluminium oxide (Al_2O_3) as the particle. Solar reflectance and atmospheric window emissivity, hence cooling performance were enhanced by incorporating composite aerogel structure with Al_2O_3 nanoparticles at varying content (10 and 20 wt.% of matrix components). Besides morphological and chemical structure analysis using SEM and FT-IR, optical features such as radiative emissivity and solar reflectance were determined by FT-IR and UV-VIS-NIR spectrometer integrated with a diffuse integrating sphere, respectively. Cooling performances were determined under simulated conditions by a designed hotplate system including sun-simulator a halogen lamp and outdoor real-life tests. Results show that SF@CNF-20Al_2O_3 exhibited the maximum cooling performance with 12.25°C and 4.14°C temperature drops for bare skin and cotton fabric according to hotplate test results. Moreover, SF@CNF-10Al_2O_3 had the maximum outdoor cooling performance of 9.4°C and 4.1°C compared to bare skin and cotton fabric, respectively. These results suggest a sustainable and efficient cooling material through upcycling of waste silk cocoons and CNFs derived from renewable biomass with Al_2O_3 nanoparticles.*

Keywords: *Radiative cooling; fibroin; cellulose nanofiber; aluminium oxide; upcycling.*

KOMPOZITNI AEROGEL MATERIJALI DOBIJENI IZ OTPADA BIOMASE ZA ODRŽIVO PASIVNO RADIJATIVNO HLAĐENJE

APSTRAKT: *Materijali za pasivno radijativno dnevno hlađenje (PRDC) privlače pažnju kao današnji inovativni materijali ublažavanjem globalnog zagrevanja i smanjenjem potrošnje energije bez ikakvog ulaganja energije. Međutim, nebiorazgradivi izvori*

polimera na bazi nafte stvaraju negativno opterećenje za životnu sredinu. U ovoj studiji, održiv i efikasan PDRC kompozitni aerogel je razvijen putem liofilizacije korišćenjem svilenog fibroina (SF) iz otpadnih čaura svilene bube, celuloznih nanovlakana (CNF) kao komponente matrice i aluminijum oksida (Al2O3) kao čestice. Solarna refleksija i emisivnost atmosferskog prozora, a samim tim i performanse hlađenja, poboljšane su ugradnjom kompozitne aerogeleve strukture sa Al2O3 nanočesticama u različitim sadržajima (10 i 20 tež.% komponente matrice). Pored analize morfološke i hemijske strukture korišćenjem SEM i FT-IR, optičke karakteristike kao što su radijaciona emisivnost i solarna refleksija određene su FT-IR i UV-VIS-NIR spektrometrom integrisanim sa difuznom integrišućom sferom, respektivno. Performanse hlađenja određene su u simuliranim uslovima pomoću projektovanog sistema grejne ploče, uključujući simulator sunca, halogenu lampu i testove na otvorenom u realnim uslovima. Rezultati pokazuju da je SF@CNF-20Al2O3 pokazao maksimalne performanse hlađenja sa padovima temperature od 12,25°C i 4,14°C za golu kožu i pamučnu tkaninu, prema rezultatima testa grejne ploče. Štaviše, SF@CNF-10Al2O3 je imao maksimalne performanse hlađenja na otvorenom od 9,4°C i 4,1°C u poređenju sa golom kožom i pamučnom tkaninom, respektivno. Ovi rezultati ukazuju na održiv i efikasan materijal za hlađenje kroz reciklažu otpadnih svilenih čaura i CNF-ova dobijenih iz obnovljive biomase sa Al2O3 nanočesticama.

Ključne reči: *Radijativno hlađenje; fibroin; celulozna nanovlakna; aluminijum oksid; reciklaža.*

1. INTRODUCTION

The escalating global energy demand, particularly for cooling applications in buildings and wearable systems, has intensified the search for passive thermal management strategies that require no energy input. PRDC has emerged as a highly promising approach, leveraging the Earth's atmospheric transparency window (8-13 μm) to dissipate heat directly into the cold outer space as infrared radiation, thereby achieving sub-ambient cooling without any electricity consumption [1]. A suitable radiative cooling material must simultaneously exhibit high solar reflectance in the UV-Vis-NIR range (0.3-2.5 μm) to minimize solar heat gain and high infrared emissivity within the atmospheric window to maximize heat dissipation [2, 3]. In recent years, many research has been conducted for developing PRDC materials by designing and optimizing emissive and solar reflective coatings using photonic crystals, metal-polymer coatings, porous polymer coatings, and textiles with nanostructures [4]. However, the fact that most of these materials are derived from petroleum-based non-biodegradable polymers creates a negative burden on the environment.

Aerogels, three-dimensional porous lightweight materials, have attracted considerable attention as a platform for engineering high-performance radiative cooling materials thanks to their low density, thermal conductivity, hierarchical porous structure, and tunable

surface features [2, 3, 5, 6]. The highly interconnected porous structure endows aerogels with excellent thermal management properties, capable of multiple scattering of incident sunlight, resulting in enhanced solar reflectance, while their large specific surface area facilitates efficient mid-infrared emission [2, 3]. However, these aerogels composed of inorganic compounds are more brittle mainly through weak interconnections between nanoclusters. These poor mechanical properties can disrupt the three-dimensional pore structure of aerogels and even severely limit their thermal performance. In contrast, although polymer aerogels have better mechanical properties, the thermal conductivity will be significantly increased, and aerogels such as polyurethane [6] and polyvinyl alcohol [7] have poor thermal insulation properties at high temperatures. Therefore, there is an urgent need to develop aerogel materials with high mechanical stability and low thermal conductivity to improve heat gain and enhance radiative cooling performance.

Silk fibroin (SF), a natural protein derived from silkworm cocoons, is an attractive biopolymer for functional material fabrication due to its abundance, biocompatibility, excellent mechanical properties, and characteristic molecular vibration bands overlapping the atmospheric transparency window. In particular, the amide I, II, and III absorption bands of SF at 1650-1230 cm^{-1} align closely with the 8-13 μm emission window, suggesting inherent infrared radiative properties and solar reflectance [2, 3]. However, the dissolution-regeneration process of silk fibers can greatly damage the hierarchical structure and natural properties of the fibers themselves, and even reduce the stability and radiative thermal management performance of the constructed aerogels. Therefore, there is a need to preserve mechanical toughness of the fibers and enhance entanglement or cross-linking between the fibers for developing stable and highly porous three-dimensional structure in aerogels. Cellulose nanofibers (CNFs), another bio-derived nanomaterial rich in surface hydroxyl groups [8], can serve as a co-matrix to reinforce SF-based aerogels, improving structural stability and promoting homogeneous porous morphology. Despite the individual merits of SF and CNF, their combination as a composite aerogel matrix for radiative cooling applications has been scarcely explored. Incorporating functional inorganic nanoparticles into biopolymer aerogels represents a promising strategy to further enhance both solar reflectance and mid-infrared emissivity. Among candidate materials, aluminium oxide (Al_2O_3) nanoparticles are particularly noteworthy due to their wide bandgap (~9 eV), strong Mie scattering of solar radiation, phonon polariton resonance generating broadband absorption at 10-15 μm, and chemical stability [1]. These properties make Al_2O_3 a compelling additive for synergistically boosting the radiative cooling performance of biopolymer composite aerogels.

Herein, a sustainable and efficient PDRC composite aerogel was developed using SF from waste silkworm cocoons, CNF as the matrix components and Al_2O_3 as the particle through freeze-drying. The influence of Al_2O_3 nanoparticle content on the microstructure, chemical composition, solar reflectance, mid-infrared emissivity, and passive cooling performance was systematically investigated. Both indoor simulations using hotplate system and outdoor real-life cooling tests were conducted to evaluate practical applicability. This work demonstrates a sustainable route toward high-performance, biomass-derived radiative

cooling aerogels with potential applications in thermal management for varying cooling systems.

2. MATERIALS and METHODS

2.1. Materials

Waste silkworm cocoons were kindly provided by Umurbey Silk Production and Design Center in Bursa, Türkiye. For SF extraction, sodium carbonate (Na_2CO_3) (ZAG Chemical, Türkiye), anhydrous calcium chloride ($CaCl_2$) (Merck, Germany), and ethanol (EtOH) (Merck, Germany) were used without purification. CNFs (Length:1-3 µm, Dia: 4-10 nm) and Al_2O_3 particles (Alpha, Purity: 99.9+%, Size: 100 nm) were supplied from Nanografi, Türkiye. All chemicals were used as received without further purification. Deionized water (Millipore, 18.25 MΩ·cm) was used for preparing all aqueous solutions.

2.2. Preparation of SF and composite aerogel

For SF extraction, the cleaned waste silkworm cocoons in small pieces were degummed by boiling in 0.5 wt.% Na_2CO_3 solutions at 95°C for 1 h (liquor ratio: 70:1) then washed with deionized water at 60°C for three times and dried at 50°C. The degummed silk fibers were immersed in a $CaCl_2$:EtOH:H_2O solution at 60°C for 6 h [9]. The separated SF fibers were obtained by centrifugal separation at 10.000 rpm for 15 min and drying. To prepare composite aerogel, SF fibers at 0.4 wt.% and 1 wt.% CNF as matrix components were dispersed in deionized water by mechanical mixing and stirring for 3 h. Subsequently, Al_2O_3 particles at varying content (10 and 20 wt.% of matrix components) were added to the mixed solution to fully dispers by additional mechanical mixing for 3 h and bath sonication for 30 min. The resultant mixtures were poured into petri dishes and rapidly frozen at -80°C for 24 h. The frozen aerogel samples were subsequently subjected to freeze-drying in a lyophilizer for 48 h. The obtained aerogel samples were names as SF@CNF and SF@CNF-xAl_2O_3, respectively. x denotes the concentration of Al_2O_3 particles.

2.3. Characterizations

The microstructure of the aerogel surface was visualized by a scanning electron microscope (SEM, Fei Quanta FEG 250) instrument at an acceleration voltage of 20 kV, 10 µA current, and 250-1000 magnification. Fourier transform infrared (FT-IR) spectra were recorded to analyze compositional structure of the samples by using a JASCO FT/IR 4700 spectrometer equipped with a diamond ATR (Attenuated total reflectance) in the 400-4000 cm^{-1} range, 2 cm^{-1} resolution, and 16 scan at room temperature. The solar reflectance spectra of the aerogel samples in the UV-Vis-NIR (190-2700 nm) range were recorded using a JASCO V-770 spectrophotometer equipped with an integrating sphere. The average values of solar reflectance were calculated according to Equations (1).

$$\bar{\rho}_{solar} = \frac{\int_{0.3\ \mu m}^{2.5\ \mu m} I_{solar}(\lambda)\cdot\rho(\lambda)\mathrm{d}\lambda}{\int_{0.3\ \mu m}^{2.5\mu m} I_{solar}(\lambda)\mathrm{d}\lambda} \quad (1)$$

Also, reflectance ($\rho(\lambda)$) and transmittance ($\tau(\lambda)$) in the range of atmospheric window wavelength (8-14 μm) were measured using a Fourier transform infrared spectrometer (Bruker VERTEX 70v) equipped with MIR integrating sphere in the diffuse reflectance mode. The average values of atmospheric window emissivity calculated according to Equations (2).

$$\bar{\varepsilon}_{IR} = \frac{\int_{8\,\mu m}^{14\,\mu m} I_{BB}(\lambda)\cdot\varepsilon(\lambda)\mathrm{d}\lambda}{\int_{8\,\mu m}^{14\,\mu m} I_{BB}(\lambda)\mathrm{d}\lambda} \quad (2)$$

where ε: emissivity, ρ: reflection, τ: transmittance, and λ: wavelength, $I_{solar}(\lambda)$: global solar intensity spectrum according to ASTM G173, I_{BB}: spectral radiance of a blackbody defined by Planck's law at temperature T.

Passive cooling properties of the aerogel samples under indoor simulation were determined by recording the temperature by thermocouples of a hotplate system simulating skin with heating power of 104 W/m^2. The hotplate system possesses simulated skin whose temperature was set at 34±0.5°C, a sun simulator halogen lamp (600 W/m^2), and a data acquisition system. After 1 min stabilizing period, temperature data of the samples were recorded with 10-second frequency during 30 min switch-on and switch-off periods. At least three replications were carried out for each sample.

Meanwhile, outdoor real-life cooling performances were tested using a home-made test setup including an aluminum foil coated polystyrene foam box in size of 20 × 20 × 12 cm^3 and temperature data logger system (KIMO KTH 320). The top opening of the insulating foam box was covered with samples, and K-type thermocouples were fixed to the bottom of the samples for recording temperature with 5-second frequency. The outdoor passive cooling tests were conducted at West Campus of Süleyman Demirel University, Isparta, Türkiye (37° 49' 42" N, 30° 31' 34"E) by taking measurements from 09:40 am to 13:45 pm in July 2025. The environmental conditions of the outdoor test were determined as 18-39°C temperature, 26-47% relative humidity, and 7.6-15.1 km/h air velocity. The solar irradiance was ranged 714-815 W/m².

3. RESULTS

In this study, biomass waste-derived composite aerogel samples with SF from waste silkworm cocoons, CNF, and Al_2O_3 as the particle through freeze-drying were produced to develop efficient and sustainable passive radiative cooling material. Microstructure and surface morphology of the SF@CNF and SF@CNF-Al_2O_3 composite aerogel samples, were visualized using SEM analysis and images were shown in Figure 1. As seen in Figure 1 (a), SF@CNF aerogel structure has been successfully produced with porous geometry. Adding CNF with rich hydroxyl groups, as co-matrix material may enhance affinity of SF and improve the connection SFs, resulting in a stable aerogel hence hierarchical porous structure [3]. Adding Al_2O_3 particles into SF@CNF matrix led to an increase in pore size, which directly proportional to the amount of nanoparticles (Figure 1 (b, c)). Relatively macroporous structure in SF@CNF-Al_2O_3 composite aerogel could derived from

disrupting high entanglement between SFs and CNF based on serving abundant hydroxyl groups on the surface of them as binding sites [2, 3] for Al_2O_3 nanoparticles.

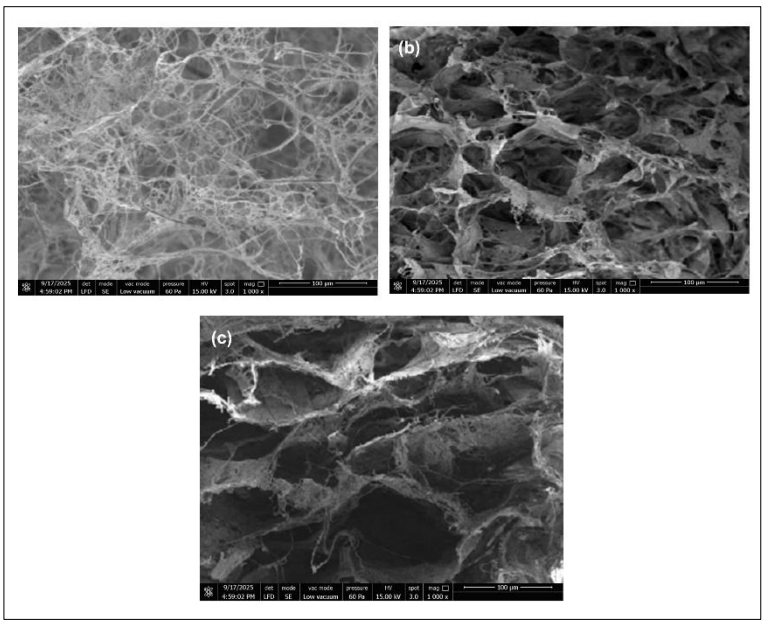

Figure 1: Surface SEM images of the SF@CNF (a), SF@CNF-10Al_2O_3 (b), and SF@CNF-20Al_2O_3 (c) composite aerogel at 1000x magnification

In order to evaluate the compositional structure of the samples, the functional groups were analyzed using FT-IR spectra. The infrared spectra of SF, SF@CNF, and SF@CNF-Al_2O_3 composite aerogel with varying particle content were illustrated in Figure 2. In the spectra of SF and all aerogel samples, the characteristic peak of SF particle such as amide I, amide II, and amide III were observed at 1651-1593, 1535, and 1233 cm^{-1}, arising from C-N stretching, C-N and N-H deformation, respectively [10, 11]. Also, SF@CNF and SF@CNF-Al_2O_3 composite aerogel samples show characteristic cellulose characteristic peaks of (-OH) stretching band at 3200-3400 cm^{-1}. Although there is a noticeable difference with Al_2O_3 particles, the broad band at 665 and 845 cm^{-1} can be assigned to bending mode of O-Al-O and Al-O stretching mode, respectively in the composite aerogel samples. The resulted composite SF@CNF-Al_2O_3 aerogel samples exhibit strong infrared absorption due to the mentioned molecular vibration peaks overlapping the atmospheric transparency window (8-13 μm) corresponded exactly to the absorption at 1250-780 cm^{-1}, contribute to higher thermal emittance thereby passive cooling performance.

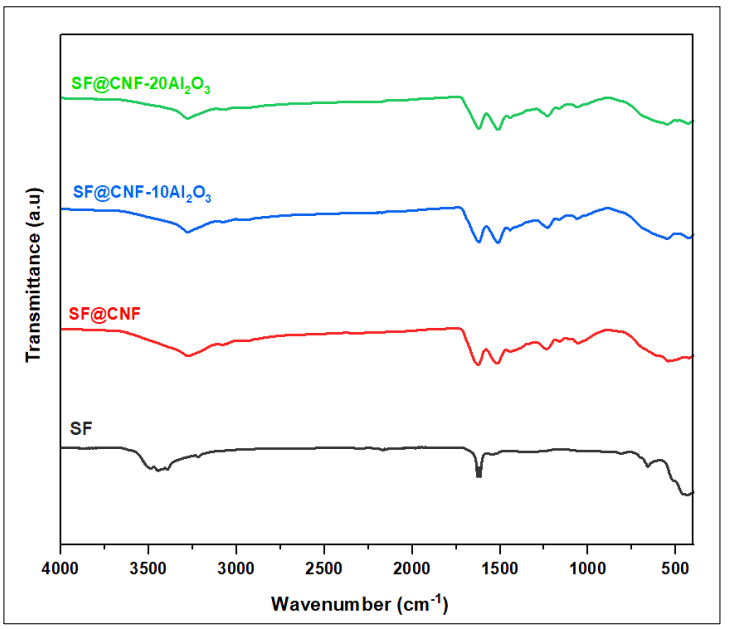

Figure 2: FT-IR spectra of degummed SF, SF@CNF, SF@CNF-10Al_2O_3, and SF@CNF-20Al_2O_3 composite aerogel

High solar reflectance and emissivity from atmospheric window are crucial for materials to get efficient passive radiative cooling. In order to evaluate solar reflectance performance, reflectance spectra of the aerogel samples in corresponding wavelength were measured and average solar reflectance values are calculated, respectively. As seen in Figure 3, Al_2O_3 particle at varying content enhanced the solar reflectance of the porous aerogel. Although the solar reflectance of the SF@CNF aerogel without particle is relatively high with an average reflectance of 88.82%, this value increased with Al_2O_3 particle and reached up to maximum value of 92.28% for SF@CNF-10Al_2O_3. The close-packed porous structure of SF@CNF aerogel without particle may resulted in relatively higher reflective interface and scattering ability inside the aerogel, thereby decreasing the thermal radiation absorption ability [12]. For composite aerogels including Al_2O_3 particle, the high light scattering properties of Al_2O_3 particles [12, 13] and porous structure of the aerogel resulted in sufficient reflection and Mie scattering of sunlight. On the other hand, increase of Al_2O_3 particle content led to decrease in the solar reflectance with a value of 91.32% for SF@CNF-20Al_2O_3, which may be due to the decrease of light scattering caused by the excess Al_2O_3 particles hindering the pore structure of the aerogel.

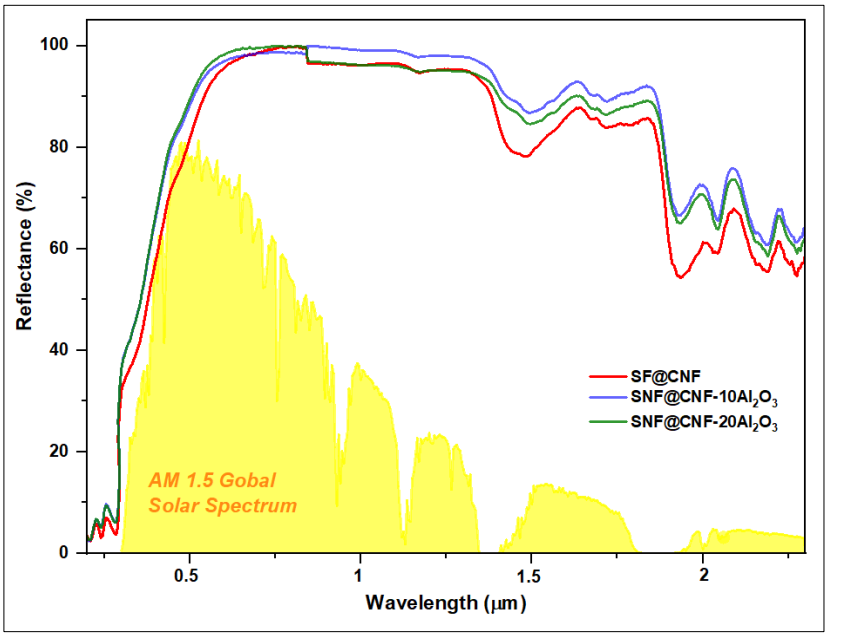

Figure 3: Solar reflectance spectrum of SF@CNF, SF@CNF-10Al_2O_3, and SF@CNF-20Al_2O_3 composite aerogel

In harmony with solar reflectance, the emissivity of the aerogel samples within the atmospheric window range (8-13 μm) enhanced with Al_2O_3 particle addition. As seen in Figure 4, SF@CNF aerogel without particle exhibited an average emissivity value of 86.63% while Al_2O_3 particle incorporation leads to an increase in infrared emissivity, reaching to a maximum value of 89.05% at nanoparticle concentration of 20%. As stated before, SF@CNF and also SF@CNF-Al_2O_3 aerogel samples had molecular vibration peaks overlapping the atmospheric transparency window (8-13 μm) corresponded exactly to the absorption at 1250-780 cm^{-1}, may resulted in higher infrared emissivity values. Compared with with similar studies including SF and CNF-based cooling materials [1-3, 12, 13], the aerogels especially SF@CNF-Al_2O_3 composites has comprehensive competitiveness, presenting the high infrared emissivity and solar reflectivity, hence passive radiative cooling performance.

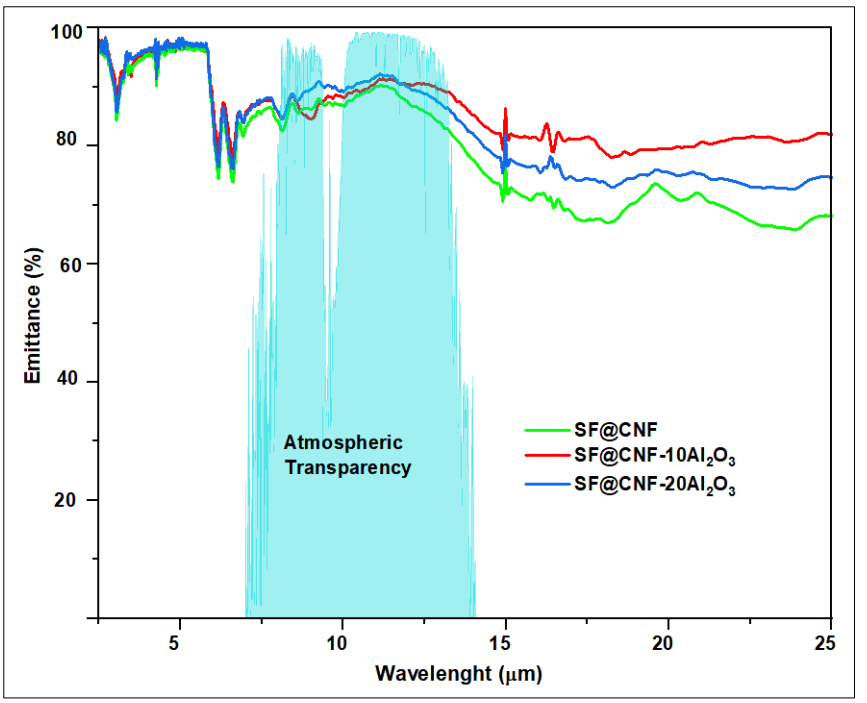

Figure 4: Mid-infrared emissivity spectra of SF@CNF, SF@CNF-10Al_2O_3, and SF@CNF-20Al_2O_3 composite aerogel

Passive cooling performances of the samples which can be calculated from the real-time temperature graphics obtained from the designed hotplate system in comparison with a single jersey cotton fabric and bare skin are given in Figure 5. According to test results, the temperature of the all samples gradually increased and reached maximum for each sample after 30 min of sunlight exposure. Benefiting from the higher solar reflectance and mid-infrared radiation emission, SF@CNF-20Al_2O_3 composite aerogel samples had a maximum temperature of 45.61°C, which is lower than all aerogel ones (49.53 and 47.87°C for SF@CNF and SF@CNF-10Al_2O_3, respectively. Under a solar intensity of 600 W/m^2, the maximum cooling performance of 12.25°C, 4.14°C, and 3.92°C temperature drops were detected for SF@CNF-20Al_2O_3 as compared to bare skin, cotton fabric, and SF@CNF, respectively. SF@CNF-Al_2O_3 composites, especially the one including 20% Al_2O_3 particles exhibited the maximum cooling performance thanks to its higher solar reflectance and mid-infrared emittance.

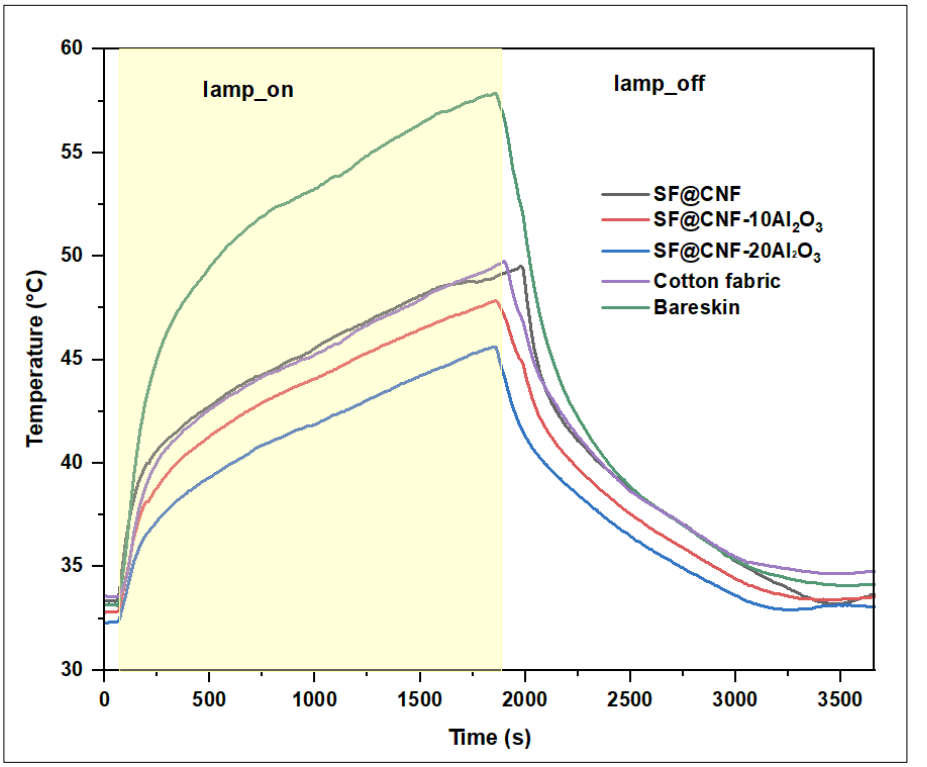

Figure 5: Real-time temperature curves of SF@CNF, SF@CNF-10Al_2O_3, and SF@CNF-20Al_2O_3 composite aerogel, cotton fabric and bare skin

The real time temperature values of the aerogel samples, cotton fabric, and bare skin, showing the outdoor cooling performances, can be seen in Figure 6. The temperature of all the samples gradually increased up to 12:15 pm and reached T_{max} for bare skin as 65°C and minimum T_{max} was recorded for SF@CNF-10Al_2O_3 as 55.6°C. T_{max} and $T_{average}$ values of the all-aerogel samples are lower than cotton and bare skin, showing their passive cooling capabilities. According to results, SF@CNF-10Al_2O_3 had the maximum cooling performance under outdoor real-life condition; namely 9.4°C and 4.1°C compared to bare skin and cotton fabric, respectively. These further reveals that SF@CNF-Al_2O_3 composite aerogel have a strong cooling effect and are expected to be a potential material for outdoor radiative cooling.

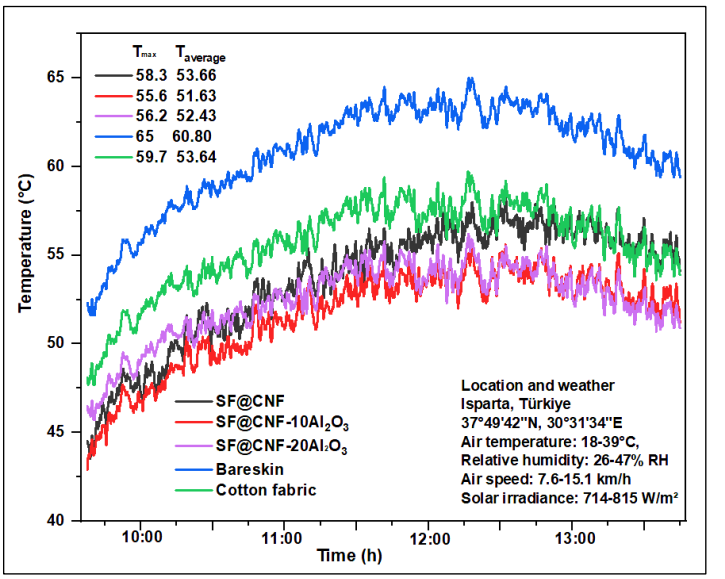

Figure 6: Outdoor-real-life cooling performance of SF@CNF, SF@CNF-10Al_2O_3, and SF@CNF-20Al_2O_3 composite aerogel, cotton fabric and bare skin

4. CONCLUSION

In this study, efficient passive cooling composite aerogels were successfully developed by combination of SF from waste silkworm cocoons-CNF and Al_2O_3 particles through freeze-drying. Solar reflectance and atmospheric window emissivity, hence cooling performance were enhanced by incorporating composite aerogel structure with Al_2O_3 nanoparticles. Under 600 W/m^2 solar irradiation in hotplate test, SF@CNF-20Al_2O_3 exhibited the maximum cooling performance with 12.25°C and 4.14°C temperature drops for bare skin and cotton fabric, respectively due to higher solar reflectance (92.28%) and mid-infrared emittance (89.05%). Outdoor tests demonstrated that under 714-815 W/m^2 solar irradiation, average temperature reduction of up to 9.4°C and 4.1°C compared to bare skin and cotton fabric, were achieved for SF@CNF-10Al_2O_3 composite aerogels. Overall, this study demonstrates that upcycling of waste silk cocoons combined with renewable biomass-derived CNF, and Al_2O_3 nanoparticles, constitutes a viable and environmentally responsible strategy for fabricating cooling materials.

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SUSTAINABILITY ASSESSMENT OF AN APPLIED METHOD FOR ENHANCING THE ACOUSTIC PROPERTIES OF HEMP-BASED TEXTILE INSULATION SYSTEMS

Scientific paper
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ABSTRACT: *The demand for sustainable and high-performance acoustic materials has led to increased interest in textile-based sound insulation systems. However, natural and recycled textile materials often exhibit lower acoustic efficiency compared to conventional synthetic insulations. This paper investigates the potential of plasma surface treatment as an environmentally friendly method to enhance the acoustic performance of textile-based insulation materials, with a particular focus on recycled textile hemp-based insulation systems. Plasma treatment modifies fiber surface morphology and chemistry, improving airflow resistivity and internal friction—key parameters influencing sound absorption and insulation. The study also evaluates the ecological implications of plasma treatment, demonstrating its advantages over traditional chemical processing methods. The results indicate that plasma-treated textiles can achieve improved acoustic performance while reducing environmental impact, making them a promising solution for sustainable building acoustics.*

Keywords: *Sustainable acoustic materials, Life Cycle Assessment (LCA), hemp- based materials, plasma treatment, sound absorption coefficients (SAC), Environment impact.*

PROCENA ODRŽIVOSTI PRIMENJENE METODE ZA POBOLJŠANJE AKUSTIČNIH SVOJSTVA TEKSTILNIH IZOLACIONIH SISTEMA NA BAZI KONOPLJE

APSTRAKT: *Potražnja za održivim i visoko efikasnim akustičnim materijalima dovela je do povećanog interesovanja za sisteme zvučne izolacije na bazi tekstila. Međutim, prirodni i reciklirani tekstilni materijali često pokazuju nižu akustičnu efikasnost u poređenju sa konvencionalnim sintetičkim izolacijama. Ovaj rad istražuje potencijal površinske obrade materijala plazmom kao ekološki prihvatljive metode za poboljšanje akustičnih performansi izolacionih materijala na bazi tekstila, sa posebnim fokusom na izolacione sisteme na bazi recikliranog tekstila od mešavine konoplje. Obrada plazmom modifikuje morfologiju i hemijski sastav površine vlakana, poboljšavajući otpornost protoua vazduha*

i unutrašnje trenje - ključne parametre koji utiču na apsorpciju zvuka i zvučnu izolaciju. Studija takođe procenjuje ekološke implikacije obrade plazmom, demonstrirajući njene prednosti u odnosu na tradicionalne metode hemijske obrade. Rezultati ukazuju da tekstil tretiran plazmom može postići poboljšane akustične performanse uz smanjenje uticaja na životnu sredinu, što ga čini perspektivnim rešenjem za održivu akustičku izolaciju u građevini.

Ključne reči: *Održivi akustični materijali, procena životnog ciklusa (LCA), materijali na bazi konoplje, tretman plazmom, koeficijenti apsorpcije zvuka (SAC), uticaj na životnu sredinu.*

1. INTRODUCTION

Increasing consumer awareness and environmental concerns have significantly influenced the development of sustainable materials in the textile industry. The entire textile life cycle—from raw material extraction to disposal—contributes to environmental degradation through high energy consumption, water usage, and chemical emissions [1], [2]. Natural fibers such as cotton, wool, and flax possess considerable ecological footprints related to cultivation and processing, while synthetic fibers present environmental challenges due to their fossil-based origins and long degradation times [1], [3]. Therefore, recycling and reuse of textile materials have become essential strategies within the framework of a circular economy [4]. In recent years, hemp fibers have gained attention as a sustainable alternative due to their low environmental impact, biodegradability, and favorable mechanical properties [5], [6]. Furthermore, the use of recycled hemp-based textiles, especially in knitted structures, contributes to sustainable material development due to their renewability, porosity, and suitability for acoustic applications [6], [7]. Plasma treatment has additionally emerged as an environmentally friendly surface modification technology because it reduces water and chemical consumption and eliminates wastewater generation associated with conventional wet processing methods [8], [9].

Increasing consumer awareness and environmental concerns have significantly influenced the development of sustainable materials in the textile industry. The entire textile lifecycle, from raw material extraction to disposal, contributes to environmental degradation through high energy consumption, water usage, and chemical emissions.

Beyond sustainability, modern textiles are increasingly required to provide functional performance, including thermal insulation and acoustic absorption. These properties are particularly relevant for applications in building materials, automotive interiors, and technical textiles.

Surface modification techniques, such as plasma treatment, have shown significant potential in enhancing fiber surface characteristics, including: increased surface roughness, improved porosity, modified airflow resistivity [18].

The aim of this study is to investigate the combined effect of plasma treatment and the incorporation of hemp-based materials on the acoustic and sustainability performance of

recycled cellulose knitted textiles. By integrating eco-friendly materials with advanced surface engineering, this research seeks to contribute to the development of next-generation sustainable acoustic insulation systems.

2. MATERIALS AND METHODS

The sustainability assessment of plasma-modified hemp knitted fabrics was conducted using the Life Cycle Assessment (LCA) methodology in accordance with ISO 14040 and ISO 14044 standards [10],[11].The analysis was based on a cradle-to-gate approach with a functional unit defined as 1 m² of hemp knitted fabric, which is a commonly applied system boundary in textile sustainability assessments [10],[13].
The LCA methodology defines the goal and scope, inventory analysis, impact assessment, and interpretation phases used in this study. The life cycle inventory (LCI) included hemp cultivation, fiber processing, knitting, and plasma surface modification. Primary data for plasma treatment were based on experimental conditions, while secondary data were obtained from literature and standard LCA databases such as Ecoinvent, which is widely used for background inventory data in environmental assessments [12], [14].The life cycle impact assessment (LCIA) was performed using standard emission factors to evaluate energy consumption, carbon dioxide emissions, water use, and chemical impact, following the impact assessment principles recommended within ISO-based LCA studies [10],[11]. The results were interpreted to identify environmental benefits and trade-offs associated with plasma modification.

2.1. Materials

The recycled hemp knitted fabrics used in our investiga- tions were a mixture of cotton and hemp 50%/50% in a form of knitted fabrics. The basic characteristics of the material used in the form of rib (1:1) knitted fabrics are: stitch density: 64–72 cm-2; thickness: 2.36–2.50 mm; surface den- sity (areal density): 950–1000 g/m2 and bulk density: 0.38–0.42 g/cm3. Hemp fibers are recognized as sustainable materials due to their low environmental footprint and favorable mechanical properties [15].

2.2. Plasma treatment

Plasma treatment is a dry, chemical-free surface modification technique used to enhance properties such as: hydrophilicity or hydrophobicity, dye uptake (reduces dye volume and wastewater) , mechanical properties , antimicrobial properties, acoustic performance [16], [17]. Plasma treatment is considered an environmentally friendly alternative to conventional wet processing due to reduced chemical consumption and lower environmental impact [17], [18]. For the modification of the cotton/hemp knitted fabrics we used the plasma treatment in the RF capacitively coupled plasma (CCP) reactor filled by the N_2 – Ar gas mixture. The reactor was placed in the cylindrical 304 stainless steel chamber. In the center of the cylinder a copper electrode was placed. In order to control gas or gas mixture purity, a vacuum system equipped with gas mass flow controllers was used. The high voltage RF generator at standard 13.56 MHz frequency was applied for RF

discharges. The argon gas was fed through mass flow controller at gas flow of 2 sccm and nitrogen gas flow was 40 sccm. The pressure of the argon gas in the chamber was 1,1 Torr and the maximal voltage was 1200 V peak to peak. The power which was used during plasma discharges was 100 W. The treated samples of materials were set in plasma reactor by using specially designed feed through connector and the treatments lasted for 5, 10, 15 and 20 minutes. In order to measure and control plasma conditions, the optical emission spectroscopy (OES) was employed. The measurements of the sound absorption coeficient (SAC) of the examined materials were performed before and after plasma treatments. We used a standard two-microphone impedance tube which has been designed as per the ISO 10534-2:1998 standard (Acoustics-Determination of sound absorption coefficient and impedance in impedance tubes-Part 2: Transfer-function method). The diameter of the tube (29 mm) was set up for measuring SAC in the high frequency range (up to 5200 Hz). The measurements of the sound absorption coeficient (SAC) of the examined materials were performed before and after plasma treatments[19].

2.3 Evaluation Metrics

The sustainability impacts were evaluated using: 1) Acoustic Performance (Absorption coefficient) ; 2) Water Footprint (WF): Volume of water consumed per kg fabric through processing steps; 3) Energy Consumption (EC): Measured in MJ/kg for fabrication and finishing; 4) Chemical Use Intensity (CUI): grams of applied chemicals per kg fabric; 5) Life Cycle Assessment (LCA): Based on cradle-to-gate modeling, estimating CO_2 equivalent emissions (kg CO_2-eq/kg fabric), Raw Material Source (Renewability and). Comparative analysis was conducted against conventional knitted cellulose textiles finished using standard wet chemical treatments.

3. RESULTS

3.1 Acoustics Properties

The SAC spectra for both untreated and the plasma treated sample, in the frequency range from 0 Hz to 5000 Hz, are presented in Figure 1. As can be seen from the figures, the knitted fabrics are charac-terized by higher SAC in the whole frequency range after the plasma treatment. The results demonstrate that plasma treatment enhances the sound absorption performance of the textile material, with optimum acoustic behavior achieved at 15 min of treatment, while prolonged exposure (20 min) causes a deterioration in SAC due to probable structural over-modification of the fibrous network. From the Figure 1 it can be seen that SAC increase afte treatment in N2-Ar gas mixture plasma about 60 % at frequency 4500 Hz and about 25 % in mid-frequency range (~1000–4000 Hz). The modification of the acoustical properties of the natural cellulose materials was related to their structural micro-mechanical changes, such as a decrease in the fibers' stiffness and an increase in their diameter. Plasma treatment modifies textile or porous materials by: increasing surface roughness, introducing micro-pores, adding functional groups (–OH, –COOH) that improve fiber interaction improving airflow resistivity (key for acoustic damping) [19]. Result is better sound absorption coefficient, especially at mid–high

frequencies. Plasma surface treatment enhances the acoustic performance of textile-based insulation materials by modifying fiber morphology and increasing airflow resistivity. This improvement enables the use of thinner or lower-density materials to achieve equivalent sound absorption, thereby reducing raw material consumption and embodied energy. Additionally, plasma treatment facilitates the substitution of synthetic insulation materials with bio-based alternatives, contributing to lower global warming potential. As a dry and low-chemical process, plasma treatment also minimizes water usage and hazardous emissions compared to conventional chemical finishing methods, resulting in an overall reduction of environmental impact [20].

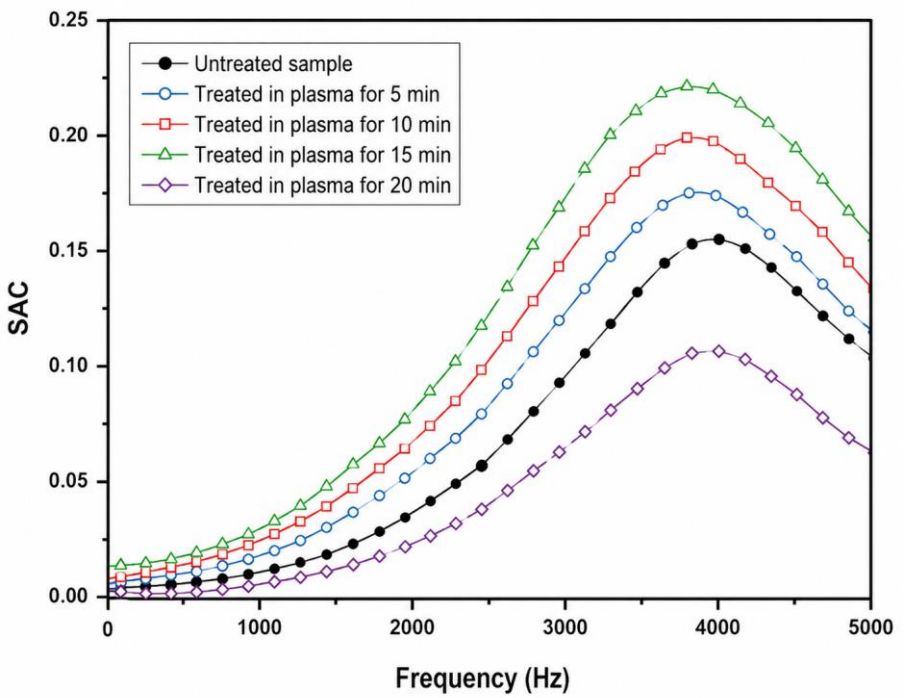

Figure 1: The SAC (sound absorption coeficient) spectra for untreated and the plasma treated sample, in the frequency range from 0 Hz to 5000 Hz

3.2 Environmental Performance

The plasma process, owing to its dry, low-energy nature, dramatically reduces the water and chemical footprint compared with traditional wet finishing. Recycling cellulose fibers circumvents virgin fiber production impacts, notably eliminating cotton cultivation's water and pesticide demands. When combined, these strategies yield a markedly lower environmental burden without sacrificing material performance.

Table 1: Environmental Performance Comparison of Conventional Textile Processing and Plasma-Treated Recycled Cellulose/Hemp Textiles

Indicator	Conventional Textile	Recycled + Plasma Treatment	Improvement	Source
Water Footprint	~8,000 L/kg	~1,200 L/kg	~85% ↓	M. Saleem et al.(2021) [21]
Energy Consumption	~60 MJ/kg	~35 MJ/kg	~42% ↓	Vanessa Pasquet et al.(2014) [22]
Chemical Use	~150 g/kg	~10 g/kg (only fiber prep.)	~93% ↓	M. Saleem et al. (2021) [21]
CO_2-eq Emissions	~15 kg/kg	~8 kg/kg	~47% ↓	Vyrkou, A. et al. (2024) [23]
Environmental footprint (µPt per 10 g cotton)	18.9	8.95	~47–53% ↓	Vyrkou, A. et al. (2024) [23]
Treatment cost (£ per 10 g cotton)	5.47	1.03	~81% ↓	Vyrkou, A. et al. (2024) [23]

Values are based on aggregated data from recent textile sustainability studies and standardized LCA models. Values for water footprint, energy consumption, chemical consumption, and CO_2-equivalent emissions are literature-based comparative indicators adapted from published sustainability reviews on plasma textile processing and used here for environmental comparison of conventional and plasma-treated cellulose/hemp textile systems. Environmental footprint (µPt) and treatment cost values are experimentally reported life-cycle assessment (LCA) results from Vyrkou et al. (2024).

3.3 Material use

Among all plant fibers, hemp is one of the most interesting because of its excellent properties, low cost, and high cellulose content. The research revealed that: the sequence of sound-absorbing performance of several fiber aggregates was cotton fiber, waste hemp fiber, wool fiber, and polyester fiber; that waste hemp fiber had excellent high-frequency sound-absorbing performance, with a maximum sound absorption coefficient of 0.95; and that the maximum sound absorption coefficient of the waste hemp fiber composite reached 0.93 [24]. Therefore, the waste hemp fiber has excellent sound-absorbing properties and has high application value in the field of sound absorption.

As presented in Figure 2, total energy required for the production of one tonne of spun fibre varies significantly in the twelve case studies with polyester consuming the most (104,479 and 126,706 MJ). It is suggested that the difference between the two polyester studies could be attributed to a difference in the PET processing method due to geographical location or an improvement in technological efficiency during the time between which the two studies were conducted. The “Polyester 1” study is more recent and represents a consistent methodology developed by Boustead (1995) for all plastics. Despite the existing variation

(22,227MJ) between both polyester studies, they clearly demonstrate the considerably larger energy requirement for production of synthetic fibre in comparison to hemp and cotton. It is important to note that the energy required for production includes the feedstock, or raw material. If the feedstock is not included, the energy requirement of polyester drops by approximately 36 per cent. However, the energy requirement of polyester is significantly greater than that of cotton and hemp, which require between 11,000 and 32,000MJ, even when allowing for large error margins. Energy requirements for hemp is from 15,009MJ for traditionally processed organic hemp to 32,622MJ for conventionally grown hemp processed through a green decortication system. In contrast to cotton, the greatest energy requirements for hemp are in the fibre production stage, as the cultivation of the crop requires fewer inputs. However, energy savings of 6,596MJ are still achieved when hemp is cultivated organically instead of conventionally. The hemp fibre production process that requires the least energy at 13,500 MJ is the traditional system of scutching, hackling, roving, drawing and wet spinning. Hemp-based materials further improve the sustainability profile of plasma-treated recycled cellulose textiles due to their relatively low production and processing costs. Techno-economic assessment demonstrated hemp fiber production and processing costs in the range of 1155–1505 USD/t **(**includes production, harvest, logistics, and processing), which makes it much closer to a real material cost for textile/acoustic applications than raw agricultural cost alone, supporting its economic feasibility as a sustainable reinforcement material for acoustic textile systems [25], [26].

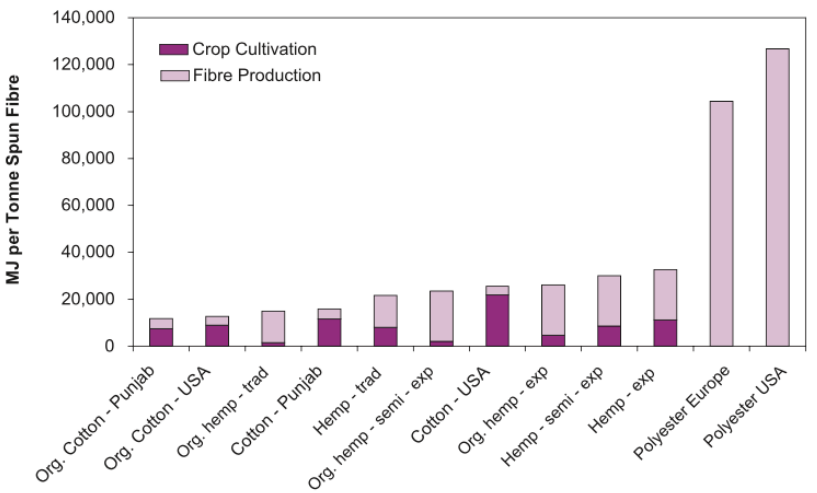

Figure 2: Total energy (in megajoules) required to produce one tonne of spun fibre [25]

3.4 Combined Sustainability Impact

The integration of plasma surface treatment with recycled hemp-based textile materials represents a highly effective strategy for developing sustainable acoustic insulation systems. Plasma treatment enhances the acoustic performance of recycled textiles, enabling them to compete with conventional insulation materials while maintaining significantly

lower environmental impact. This approach supports the transition toward circular economy principles in the construction sector and contributes to the development of environmentally responsible noise control solutions.

4. CONCLUSION

This survey highlights the potential of sustainable acoustic materials as viable alternatives to conventional insulation systems. Among these, recycled textile materials stand out due to their environmental benefits, but their performance limitations must be addressed. Plasma surface treatment emerges as an effective and environmentally friendly solution for enhancing the acoustic properties of recycled textiles. The combined approach offers a pathway toward high-performance, low-impact acoustic insulation materials suitable for modern sustainable construction.

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TREATMENT OF WASTEWATER OF THE TEXTILE INDUSTRY IN SERBIA AS A PRECONDITION FOR SUSTAINABLE MANAGEMENT OF WATER RESOURCES

Scientific paper,
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ABSTRACT: *The textile industry is one of the main sources of environmental pollution, primarily due to the types and amounts of waste water it generates. Estimates indicate that around 20% of global water pollution comes from textile manufacturing plants. These wastewaters generally contain a high level of microfibers and textile dust aerosols, various types of organic and inorganic hard-to-degrade chemical substances, pesticides, and heavy metals. The frequent occurrence of uncontrolled discharge of wastewater from textile industry facilities, which seriously disrupt water ecosystems, has conditioned the textile industry sector to establish more efficient systems for wastewater treatment and more responsible behavior towards the preservation of water quality and the environment. In this regard, this paper provides an overview of environmentally acceptable methods of processing wastewater from the textile industry, which can represent solutions for mitigating the negative effects of these waters on the environment.*

Keywords: *textile industry, sustainability, water resources, wastewater.*

PREČIŠĆAVANJE OTPADNIH VODA TEKSTILNE INDUSTRIJE U SRBIJI KAO PREDUSLOV ODRŽIVOG UPRAVLJANJA VODNIM RESURSIMA

APSTRAKT: *Tekstilna industrija predstavlja jedan od glavnih izvora zagađenja životne sredine, pre svega zbog tipova i količina otpadnih voda koje generiše. Procene ukazuju da oko 20% globalnog zagađenja voda dolazi iz proizvodnih tekstilnih pogona. Ove otpadne vode uglavnom sadrže visok nivo mikrovlakna i aerosola tekstilne prašine, različitih vrsta*

organskih i neorganskih teško razgradivih hemijskih supstanci, pesticida, i teških metala. Učestala pojava nekontrolisanog ispuštanja otpadnih voda iz postrojenja tekstilne industrije, koji ozbiljno narušavaju vodne ekosisteme uslovila je sektor tekstilne industrije na uspostavljanje efikasnijih sistema za tretman otpadnih voda i odgovornije ponašanje prema očuvanju kvaliteta voda i životne sredine. S tim u vezi u ovom radu dat je pregled ekološki prihvatljivih metoda prerade otpadnih voda tekstilne industrije koje mogu predstavljati rešenja za ublažavanje negativnih uticaja ovih voda na životnu sredinu.

Ključne reči: *tekstilna industrija, održivost, vodni resursi, otpadne vode.*

1. INTRODUCTION

The interaction between anthropogenic activities and natural ecosystems during the historical development of mankind has resulted in intense changes in the structure and functionality of the environment. Demographic growth, urbanization and accelerated industrial-technological modernization are the key drivers of these processes, where the continuous exploitation of natural resources and increased consumption of energy and raw materials additionally intensify the anthropogenic pressure on ecological systems [1].

Within the industrial sources of pollution of water resources, the textile industry occupies a particularly important place as one of the largest generators of pollutants. This sector is characterized by the intensive application of synthetic and organic chemical compounds throughout the entire life cycle of textile products, including the stages of production, chemical modification, use and post-consumer waste management [1, 2].

Technological processes in the textile industry, such as sumercerization, bleaching, dyeing, refining and finishing of textile fibers, are characterized by a particularly high level of process water consumption. According to some data, the total amount of water used during the processing of a kilogram of textile material is approximately equal to the koikin of 100-200 liters of water. At the same time, complex streams of industrial wastewater are generated, whose chemical composition and physical-chemical characteristics depend on the type of fibers, applied technology and used chemical reagents. As much as 60 to 90% of the total water used is used when rinsing and washing textiles, which indicates a great potential for the implementation of water recirculation, regeneration and reuse systems within closed production processes [3].

Wastewater often shows high concentrations of dyes, heavy metals, surfactants, organic pollutants and other toxic substances, which is why they require the application of advanced purification technologies. In this sense, various physical-chemical, biological and integrated hybrid processes are used with the aim of decontamination of wastewater and potential valorization of the chemical components present [4,5].

The traditional approach to the management of textile wastewater was based primarily on its controlled release into natural recipients. However, the limited efficiency of conventional treatment systems and the continuous discharge of highly loaded industrial effluents have led to the degradation of aquatic ecosystems, the reduction of biodiversity, the disruption of the ecological balance and increased risks to public health. The modern

development of environmental engineering and waste water treatment technologies has directed the focus towards the principles of circular economy and sustainable management of water resources. Such a transformation is encouraged by increasingly strict international environmental standards, regulatory frameworks and environmental protection policies that promote water recycling, waste minimization and the reduction of the environmental impact of industrial plants.
Consequently, improving the efficiency of textile wastewater treatment systems has become one of the central research and engineering issues in the fields of environmental engineering, hydraulics, and environmental management. The main goal of these activities is to reduce the anthropogenic burden on natural resources and develop ecologically sustainable industrial processes.

2. INDUSTRIAL WASTEWATER

As one of the most important branches of the processing industry, the textile industry also belongs to the group of the most risky in terms of environmental and health safety. Excessive use of natural resources, primarily water and energy, as well as the use of chemicals in the dyeing and processing processes, place this sector of the processing industry at the very top of the list of the biggest polluters. According to United Nations reports, this sector generates more carbon dioxide emissions than international aircraft and maritime transport [6].
Based on the data of the Republic Institute of Statistics, shown in Table 1, the total amount of wastewater generated from industrial production processes in 2024 was 112 million m³. Of this, a significant share originates from the processing industry sector (36.6%), [7] with a large share of wastewater originating from the textile industry.

Table 1: Wastewater in the industrial sector, 2024

Republic of Serbia			**mil.m³**
Sector	**Total**	**Unpurified**	**Purified**
Total [1)]	**112**	**82**	**30**
C - Manufacturing	41	15	26

[1)]The field of collection, treatment and disposal of waste is included

Based on the aforementioned data, it is evident that there is a significant amount of untreated water that is directly or indirectly discharged into the recipients, thereby questioning the quality of water resources and the general environment. In order to prevent further deterioration of water quality and environmental degradation, legal and by-law frameworks were adopted that define emission limit values for different categories of pollutants. These regulations refer to technological wastewater that must be purified before discharge into the sewage system, as well as to technological and other wastewater that is directly discharged into natural and artificial waterways. These measures are necessary to preserve ecological standards and integral aquatic ecosystems [8].
According to the report of the Environmental Protection Agency, the textile industry's production plants mostly emit wastewater containing high concentrations of oil and fat, as well as increased pH values due to the presence of alkali and azo dyes. The concentration

of chemical substances in wastewater depends on the processing method and the specifics of production processes, which can be complex and demanding, especially in the stages of dyeing and fine processing of textiles. These processing steps often involve the use of additives such as phosphonates, polyacrylates and maleic acid copolymers. Table 2 shows the measured values of wastewater emissions from various production processes of the textile industry at the discharge point. This information is crucial for understanding the environmental impact and implementing adequate wastewater management measures. The tests were carried out during 2024, and the data refer to waste water from the production process of the textile industry, which is discharged into recipients on the territory of the Jablanica administrative district.

Table 2: Measured values of wastewater emissions from production processes of the textile industry at the point of discharge into surface waters [9]

Sample name:	**Waste water - Textile industry**			
Field test data				
Test parameters	**Unit of measurement**	**Determined value**	**Permissible value**	**Test method**
Air temperature	°C	20,2	ND	US EPA 170.1:1974
Water temperature	°C	26,4	40,0	SRPS H.Z1.106:1970
pH value	-	11,65	6,50-9,00	SRPS EN ISO 10523:2016
Oil and fat content	mg/l	56.80	40	EPA 1664 revision A, 1999
Ammonia (NH_3) content	mgN/l	<5	10	SMEWW 4500 NH3 C 24th edition, 2022
Content of anionic detergents	mg/l	0.17	10	SMEWW 5540 C 24th edition, 2022

Due to the high content of various toxic and dangerous components, industrial wastewater especially requires specialized treatment procedures and wastewater treatments, including physical-chemical, biological and membrane processes, in order to ensure their safe disposal or deployment in the environment, in accordance with current legal regulations and standards for environmental protection.

3. WASTEWATER PURIFICATION IN THE TEXTILE INDUSTRY

Based on data from the Republic Institute of Statistics, a total of 30 million m³ of waste water was treated in 2024. The degree of purification was organized in several stages, where the first stage included 56.2% of the treated quantity, the second stage 22.5%, while the third stage covered 21.3%. The sectoral analysis shows that production processes in metallurgy (16.8%) have the largest share of purified water, followed by the food industry (16.2%), the chemical industry (15.0%) and the paper and paper products industry (11.0%). Other industrial branches, including the textile industry, make up the remaining 41.0% [6].

Wastewater treatment in the textile industry includes three key stages: primary, secondary and tertiary treatment. Each of these stages is aimed at removing specific types of pollutants, resulting in better quality water. Primary treatment focuses on the elimination of suspended solids, floating debris and coarse particles. Secondary treatment reduces the concentration of oxygen-demanding chemicals as well as dyes. Tertiary treatment aims to eliminate residual contaminants that are still present after the previous stages of treatment. Given that synthetic dyes are resistant and non-biodegradable, their removal represents a significant challenge for physical, chemical and biological treatments. Significant efforts have been made to develop advanced treatment methods that are effective, economical, flexible and easy to apply; however, many of these technologies can be expensive, especially when dealing with large amounts of waste. Some of those methods used in recent production processes are: adsorption, membrane filtration, electrochemical processes and oxidation processes.

Adsorption methods are key physico-chemical processes in the treatment of textile waste water, because they enable the selective elimination of organic and inorganic pollutants through their binding to highly porous adsorbents with developed surface active centers. Adsorption is realized through physisorption (Van der Waals forces, hydrogen bonds) and chemisorption (covalent, coordination bonds, complex formation) [10]. Biosorption uses microbial biomass to immobilize contaminants within cellular matrices.

Primary adsorbents include activated carbon, biochar, chitosan, phyllo-silicates, ion exchange resins and zeolites. Modern directions of development are focused on low-budget, agro-industrial derivative sorbents and multifunctional hybrid materials for simultaneous adsorption of dyes and heavy metals. Nanoscale adsorbents with high specific surface area and heterogeneous porous structure (micro-, meso-, macropores) allow increased sorptive efficiency and kinetics. Metal-oxide composites (Fe_3O_4, TiO_2, MnO_2) contribute to synergistic effects and improved performance. Adsorption efficiency depends on granulometry, adsorbent morphology, contaminant concentration, temperature, ionic strength, pH value and process hydrodynamics [11].

Activated carbon with microporous architecture and specific surface area up to 500 m^2/g is synthesized by thermal/chemical activation from coal and biomass. In the textile industry, it is used in powder form (PAC) and granulated (GAC), with the possibility of regeneration through chemical, thermal or steam treatment, which optimizes the economy of the treatment.

Membrane technologies, including microfiltration, ultrafiltration, nano-filtration and reverse osmosis, operate on the principle of pore size and selective separation based on the diffusive and electrochemical properties of the membranes. Polymeric and ceramic membranes allow efficient removal of dispersed colors, suspended substances and ionized substances [12].

Electrochemical processes, especially electrocoagulation, are based on the in situ formation of metal hydroxides from the electrode that adsorb and precipitate pollutants, including heavy metals and organic pollutants. This method has high efficiency (>95%), reduces generated waste and enables continuous operation with parameter control, although it requires regular replacement of electrodes and control of oxide layers [13].

Advanced oxidation processes (AOP) use hydroxyl radicals to mineralize difficult-to-degrade organic compounds. These include ozonation, UV/H_2O_2 treatments and photo-Fenton processes. Ozone oxidation is environmentally friendly and effective in decolorization and disinfection, with pH-dependent mechanisms of direct and indirect free radical oxidation [14, 15]. The use of photocatalysts based on nano-TiO_2 enables the generation of reactive radicals under UV or solar light, which promotes the decomposition of organic load and reduces BOD and COD [16].
In summary, the integration of adsorption systems, membrane processes, electrochemical treatments and AOP represents a modern holistic approach to the treatment of complex textile wastewater, with an emphasis on economically viable and ecologically optimized technologies.

4. CONCLUSION

Modern systems for purification of industrial effluents include different levels of treatment: primary, secondary and tertiary. First of all, they are based on mechanical processes aimed at removing suspended particles, sediments and coarse dispersed substances, followed by the application of biological and chemical procedures for reducing organic load, reducing biochemical oxygen consumption (BOD) and chemical oxygen consumption (COP), as well as the elimination of dissolved organic substances and color pollutants.
Advanced treatment technologies, which are particularly highlighted in current research, are aimed at eliminating residual micropollutants and refractory organic compounds that remain after conventional treatment.
By integrating these high-performance technological solutions, a significant improvement in the degree of contaminant removal is achieved, which leads to an improvement in the quality of treated effluents and compliance with modern environmental regulations. This approach not only contributes to sustainable development, but also to the rational use of water resources, which encourages the transition towards resource-efficient and environmentally responsible industrial systems.
This paper presents an integrated overview of sustainable methods and techniques of wastewater treatment from the textile industry. These innovative approaches aim to optimize the treatment process, ensuring that the treatment of wastewater from the textile industry meets the strict standards required for environmental sustainability. By adopting these advanced methods, the textile industry can significantly reduce its environmental impact, contributing to the broader goal of sustainable water management. The joint efforts of all stakeholders – industry, researchers and policy makers – can continue to drive the transformation towards a more sustainable and environmentally friendly textile industry.

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ENVIRONMENTAL AWARENESS OF THE IMPACT OF THE TEXTILE INDUSTRY ON THE ENVIRONMENT – STUDENTS' ATTITUDES

Professional paper
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ABSTRACT: *The textile industry has a significant impact on the environment through the consumption of water, energy, and chemicals, as well as through the generation of textile waste. The aim of this paper is to examine students' environmental awareness of the impact of the textile industry on the environment, as well as their attitudes and willingness to adopt more sustainable consumer behavior. The research was conducted using a survey method on a sample of 57 students from North Mitrovica. The questionnaire included questions about the frequency of clothing purchases, awareness of the environmental consequences of textile production, willingness to buy sustainable products, and participation in recycling activities. The results show that students generally recognize the negative impact of the textile industry, but that environmental criteria are still not dominant when purchasing clothing. It is concluded that additional education and clearer consumer information about sustainable textile products are needed.*

Keywords: *textile industry, environment, environmental awareness, students.*

EKOLOŠKA SVEST O UTICAJU TEKSTILNE INDUSTRIJE NA ŽIVOTNU SREDINU – STAVOVI STUDENATA

APSTRAKT: *Tekstilna industrija ima značajan uticaj na životnu sredinu kroz potrošnju vode, energije i hemikalija, kao i kroz nastanak tekstilnog otpada. Cilj ovog rada je da se ispita ekološka svest studenata o uticaju tekstilne industrije na životnu sredinu, kao i njihovi stavovi i spremnost za održivije potrošačko ponašanje. Istraživanje je sprovedeno primenom anketne metode na uzorku od 57 studenata iz Severne Mitrovice. Upitnik je obuhvatio pitanja o učestalosti kupovine odeće, informisanosti o ekološkim posledicama tekstilne proizvodnje, spremnosti za kupovinu održivih proizvoda i učešću u akcijama reciklaže. Rezultati pokazuju da studenti uglavnom prepoznaju negativan uticaj tekstilne industrije, ali da ekološki kriterijumi još uvek nisu dominantni pri kupovini odeće.*

Zaključuje se da je potrebna dodatna edukacija i jasnije informisanje potrošača o održivim tekstilnim proizvodima.
Ključne reči: *tekstilna industrija, životna sredina, ekološka svest, studenti.*

1. INTRODUCTION

The textile industry is one of the significant economic sectors, but at the same time it is a sector that creates considerable environmental pressures. The system of production and consumption of textiles is highly globalised with millions of producers and billions of consumers spread across the world in highly linear value chains involving raw material extraction, production, transportation, consumption and after-use disposal [4]. The textiles industry employs millions of people worldwide, making it among the largest in the world and an important part of Europes manufacturing industry. However, textile production and consumption cause significant environmental, climate and social impacts by using resources, water, land and chemicals and emitting greenhouse gases and pollutants [2]. Textile consumption in the EU increased from 17 kg per person in 2019 to 19 kg per person on average in 2022. At the same time, around 12 kg of clothing per person is dumped each year in the EU [3].

2. ENVIRONMENT AND CIRCULARITY OF TEXTILE

In the context of Serbia, as an upper-middle-income economy and a country in the process of aligning its environmental policies with European Union standards, the issue of sustainable textile consumption is particularly important. Although environmental regulations and circular economy principles are increasingly emphasized, their practical implementation also depends on the awareness and behavior of consumers.
To achieve a successful circular economy, circularity principles must be integrated across every stage of the value chain, spanning from initial design and production to the final consumer [1]. The modern textile industry focuses on preserving the value of garments, fabrics, and fibers, ensuring they are reintroduced into the system once their utility is maximized. This requires shifting from the resource-heavy and waste-generating "fast fashion" model toward "slow fashion." This sustainable alternative encourages purchasing second-hand items, supporting local small-scale manufacturers, repairing existing wardrobe pieces, and investing in high-quality clothing with a longer lifespan. By reducing production volumes, slow fashion delivers superior quality garments manufactured under ethical working conditions, while significantly minimizing waste.
Young people, especially students, represent an important group in this process, since their purchasing habits, attitudes toward sustainability, and willingness to change consumption patterns may influence future demand for environmentally responsible textile products. Therefore, examining students' attitudes can provide useful insight into the level of environmental awareness related to textile consumption.

2. METHODOLOGY

The research was conducted with the aim of examining students' environmental awareness of the impact of the textile industry on the environment, as well as identifying their attitudes, habits, and willingness to adopt more environmentally responsible behavior when purchasing and using clothing. Special attention was paid to students' awareness of the negative consequences of textile production, the frequency of clothing purchases, their attitudes toward environmentally friendly textile products, and the barriers to their wider use.

The survey method was applied in the research. A structured questionnaire, designed for the purposes of this paper, was used as the research instrument. The questionnaire contained closed-ended questions and statements that respondents evaluated using a five-point Likert scale. This made it possible to measure the degree of respondents' agreement with statements related to environmental awareness, consumer habits, and willingness to engage in sustainable behavior. The research sample consisted of 57 students from North Mitrovica. The respondents were selected as the target group because students represent a young, educated population that actively consumes textile products and may play an important role in the future development of sustainable consumption patterns. The research was anonymous, and participation was voluntary. The collected data were processed using descriptive statistics. The results are presented through the percentage distribution of responses for each individual question and statement. In Table 1 are presented basic demographic data of respondents.

Table 1: Basic demographic data of respondents

X	n	%
Age		
19-24	45	78,95
25-30	12	21,05
Gender		
Male	25	43,86
Female	32	56,14
Study level		
Academic	47	82,46
professional	10	17,54

A limitation of the research is reflected in the relatively small and locally limited sample; therefore, the results should be interpreted as indicative rather than generally applicable to the entire student population.

3. RESULTS AND DISCUSSION

For the question "How often do you buy clothes?" on *Figure 1*, the largest share of respondents, 38.60%, stated that they buy clothes once every 2–3 months. A slightly lower

percentage, 33.33%, reported buying clothes once a month or more often. These results indicate that a significant proportion of the student population purchases clothes relatively frequently. A moderate frequency of clothing purchases was recorded among 17.54% of respondents, who buy clothes several times a year. A smaller number of students stated that they buy clothes rarely (7.02%), while only 3.51% of respondents buy clothes only when necessary.

The obtained results show that most students demonstrate noticeable consumer activity regarding clothing purchases. In total, 71.93% of respondents buy clothes at least once every 2–3 months (*Fig. 1*), which may indicate the strong influence of fashion trends, clothing availability, and youth consumer habits. From the perspective of sustainable development, this pattern of consumption is important because more frequent clothing purchases may contribute to increased consumption of textile products, the generation of textile waste, and greater pressure on the environment. On the other hand, the relatively small percentage of respondents who buy clothes rarely or only when necessary suggests that a more sustainable form of consumption is not dominant among students. These findings confirm the need to strengthen young people's environmental awareness, particularly regarding the consequences of excessive clothing purchases, fast fashion, and the importance of extending the life cycle of textile products.

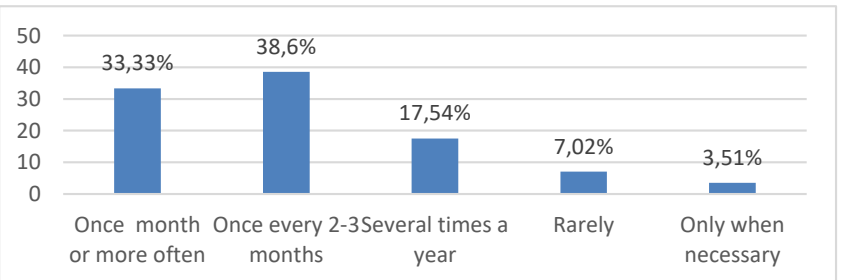

Figure 1: How often you buy clothes?

The results show that most respondents are aware that the textile industry can have a negative impact on the environment, as 49.12% of students agree and 8.77% strongly agree with the statement (*Fig.2*). Overall, 57.89% of respondents express a positive attitude, indicating a certain level of awareness of the environmental consequences of the textile industry. However, a significant percentage of students, 38.60%**,** selected the neutral or unsure option, which suggests that part of the student population may be insufficiently informed or may not clearly understand this issue. Only 3.51% of respondents disagree with the statement, while none strongly disagree. These results indicate that students generally have a basic awareness of the negative environmental impact of the textile industry, but they also show that there is room for further education on this topic.

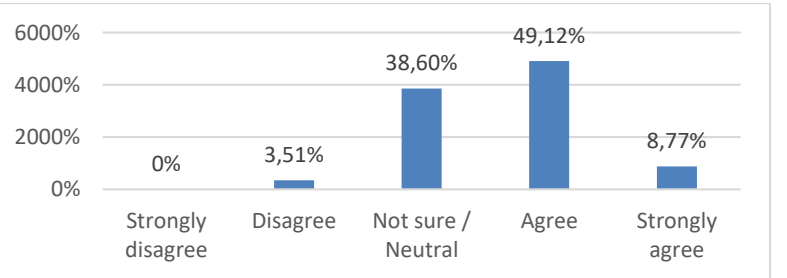

Figure 2: I am aware of the fact that the textile industry can have a negative impact on the environment

The results show that students' opinions on this statement are divided. On *Figure 3* there are presented the highest percentage of respondents, 33.33%**,** agree that clothing production can require significant consumption of water, energy, and chemicals. An additional 12.28% strongly agree with this statement. This means that a total of 45.61% of students demonstrate awareness of the resource-intensive nature of clothing production. However, a significant share of respondents, 26.32%**,** selected a neutral response, indicating uncertainty or insufficient information about this aspect of the textile industry. At the same time, 28.07% of respondents disagree or strongly disagree with the statement, which shows that a certain number of students lack knowledge about the consumption of water, energy, and chemicals in clothing production. These results indicate the need for additional education of students about the environmental consequences of textile production, especially regarding the consumption of natural resources and the use of chemicals.

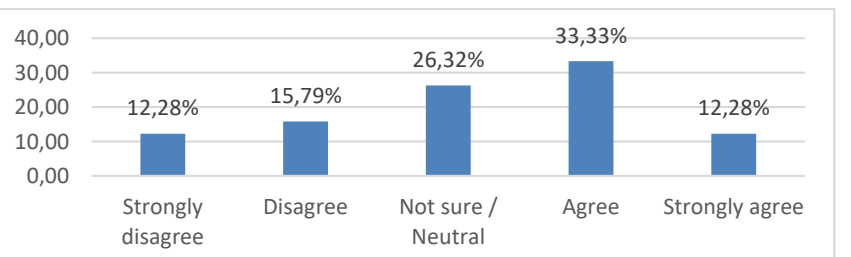

Figure 3: I know that clothing production can require significant consumption of water, energy, and chemicals

The results show that most respondents pay attention to the composition of the material when buying clothes (*Fig. 4*). The highest percentage of students, 54.39%**,** agree with the statement, while an additional 17.54% strongly agree. This means that a total of 71.93% of respondents show interest in the material composition of the clothes they purchase. A neutral attitude was expressed by 8.77% of respondents, while 19.30% disagree or strongly

disagree with the statement. These results indicate that most students show a certain level of attention to the characteristics of textile products, which may represent a good basis for developing more environmentally responsible consumer habits. However, the fact that nearly one fifth of respondents do not pay attention to material composition points to the need for additional information about the importance of materials, the origin of textiles, and their impact on the environment.

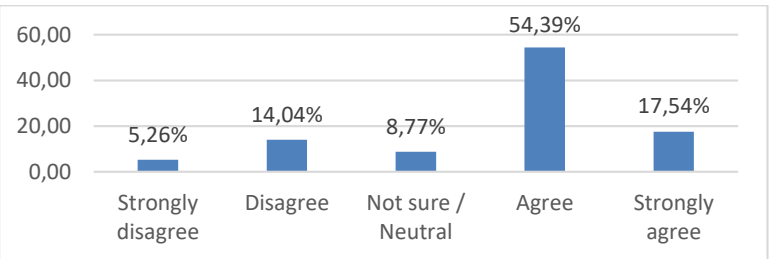

Figure 4: When buying clothes, I pay attention to the composition of the material

The results show that students pay considerably less attention to the environmental friendliness of a product when buying clothes (*Fig. 5*). The highest percentage of respondents, 35.09%**,** expressed a neutral attitude, which indicates uncertainty or insufficient information about how to recognize an environmentally friendly textile product. Total of 26.32% of respondents agree with the statement, while only 3.51% strongly agree, meaning that a total of 29.83% of respondents pay attention to this aspect of purchasing. In contrast, 28.07% disagree and 7.02% strongly disagree, meaning that a total of 35.09% of students do not pay attention to the environmental friendliness of clothing. These results indicate that, although a certain level of environmental awareness exists among some students, environmental criteria are still not a dominant factor when buying clothes. This confirms the need for additional education, clearer labeling of sustainable products, and greater availability of information about the environmental impact of textile products.

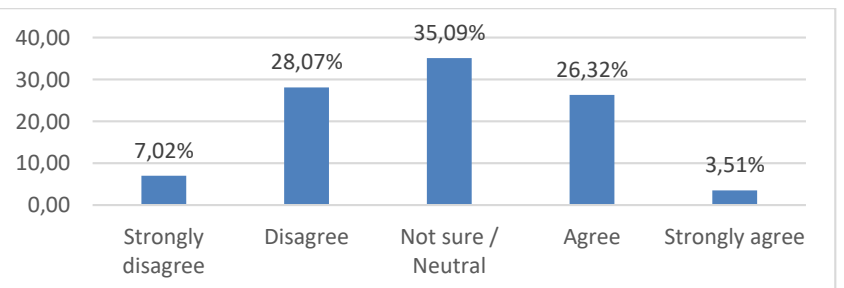

Figure 5: When buying clothes, I pay attention to whether the product is environmentally friendly

On *Figure 6*, we show a relatively high level of students' willingness to buy clothes made from recycled or sustainable textile materials, even if they are more expensive. 40.35% of respondents agree with the statement, while 15.79% strongly agree, which means that a total of 56.14% of students express a positive attitude toward purchasing sustainable clothing despite a higher price. A neutral attitude was expressed by 31.58% of respondents, which may indicate uncertainty or that the decision depends on the actual price difference, product quality, and available information. A smaller percentage of respondents, 12.28%**,** disagree or strongly disagree with the statement. These findings indicate that most students are willing to adopt more environmentally responsible consumer behavior, but also that price remains an important factor that may influence the final purchasing decision.

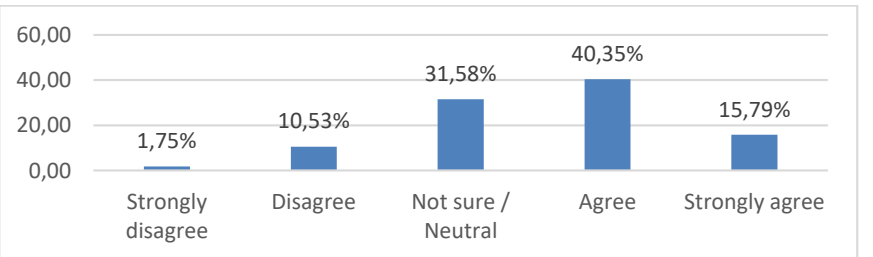

Figure 6: I am willing to buy clothes made from recycled or sustainable textile materials, even if they are more expensive.

The results show a high level of students' willingness to participate in campaigns for collecting, donating, or recycling old clothes (*Fig. 7*). More than half of the respondents, 52.63%**,** agree with the statement, while 26.32% strongly agree. This means that a total of 78.95% of students express a positive attitude toward such activities. A neutral attitude was expressed by 17.54% of respondents, while only 3.51% disagree, and none of the respondents strongly disagree. These results indicate that students show a strong willingness to take part in practical sustainability-related activities connected with textiles. This finding may provide a good basis for organizing campaigns for collecting, exchanging, donating, and recycling clothes at faculties and within the local community.

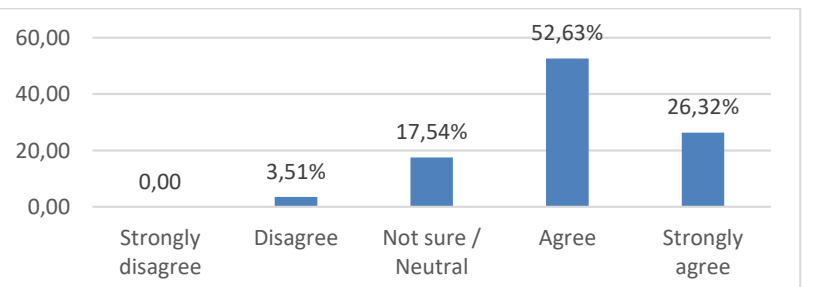

Figure 7: I am willing to participate in campaigns for collecting, donating, or recycling old clothes

Figure 8 show that half of the respondents recognize price as an important barrier to buying environmentally friendly clothing. 29.82% of students agree with the statement, while 21.05% strongly agree, which makes a total of 50.87% of respondents. A neutral attitude was expressed by 17.54% of students, which may indicate that price is not the only decisive factor, but that the decision also depends on quality, availability, and trust in environmental labels. On the other hand, 22.81% of respondents disagree and 8.77% strongly disagree with the statement, meaning that a total of 31.58% do not consider price to be the main barrier. These results indicate that price is a significant factor when purchasing sustainable clothing, but not the only barrier. Therefore, other factors such as information, product availability, and consumer trust in manufacturers' claims should also be considered.

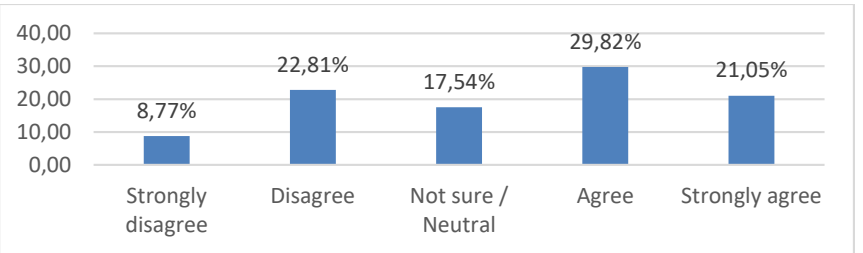

Figure 8: Price is the main barrier to buying environmentally friendly clothing.

The results on *Figure 9* show a very high level of agreement among students with the statement that clothing manufacturers should provide clearer information to consumers about the environmental impact of their products. The highest percentage of respondents, 63.16%**,** agree with this statement, while 29.82% strongly agree. Overall, as many as 92.98% of respondents support the need for clearer information about the environmental impact of textile products. A neutral attitude was expressed by 5.26% of respondents, while only 1.75% disagree, and none of the respondents strongly disagree with the statement. These results indicate that students recognize the importance of transparency in the textile industry and believe that clearer information can contribute to more responsible consumer behavior when purchasing clothing.

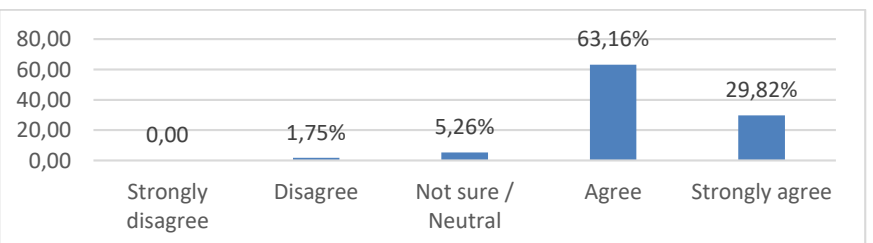

Figure 9: I believe that clothing manufacturers should provide clearer information to consumers about the environmental impact of their products

The results shown on *Figure 10* that most students believe that individuals can contribute to reducing the negative environmental impact of the textile industry through their consumer habits. 43.86% of respondents agree with the statement, while 17.54% strongly agree, which means that a total of 61.40% of students express a positive attitude. A neutral response was given by 22.81% of respondents, which may indicate a certain level of uncertainty or an insufficiently clear understanding of the personal role of consumers in this process. On the other hand, 10.53% of respondents disagree and 5.26% strongly disagree with the statement, meaning that a total of 15.79% do not recognize a significant impact of individual consumer habits. These results indicate that students have a developed awareness of the importance of personal responsibility and the role of consumers in improving the sustainability of the textile industry, but also that there is a need to further strengthen understanding of the relationship between everyday purchasing decisions and environmental protection.

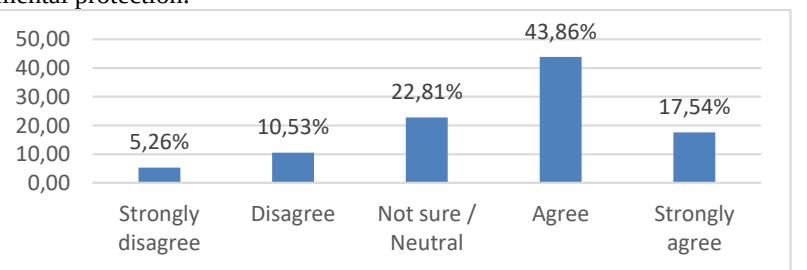

Figure 10: I believe that individuals can contribute to reducing the negative environmental impact of the textile industry through their consumer habits.

4. CONCLUSION

The research showed that students buy clothes relatively often, since the largest share of respondents purchase clothes once a month or once every two to three months. This consumption pattern may be associated with the influence of fashion trends, the availability of clothing, and the habits of young consumers. From the perspective of sustainable development, frequent clothing purchases may contribute to increased consumption of textile products, the generation of textile waste, and greater pressure on the environment.

A positive finding is the fact that most students pay attention to the composition of materials when buying clothes. However, a significantly smaller percentage of respondents pay attention to whether the product is environmentally friendly. This indicates that students take into account certain characteristics of the clothing they purchase, but that environmental criteria are still not a dominant factor in making purchasing decisions. The reasons for this may include a lack of information, unclear product labeling, insufficient availability of sustainable clothing, or the limited purchasing power of the student population.

The results also show that students are willing to adopt more environmentally responsible behavior. More than half of the respondents are willing to buy clothes made from recycled or sustainable textile materials, even if they are more expensive. A particularly high level

of willingness was observed regarding participation in campaigns for collecting, donating, and recycling old clothes. This finding indicates that students can be an important target group for organizing activities aimed at reducing textile waste and promoting sustainable consumption.

Price proved to be a significant, but not the only, barrier to purchasing environmentally friendly clothing. In addition to price, product availability, trust in manufacturers' claims, and the quality of information provided to consumers also play an important role. A very high percentage of respondents believe that clothing manufacturers should provide clearer information to consumers about the environmental impact of their products. This confirms the importance of transparency, clear labeling, and reliable information in the process of making responsible consumer decisions.

Based on the obtained results, it can be concluded that students have a basic level of environmental awareness regarding the impact of the textile industry on the environment, as well as a willingness to engage in certain forms of sustainable behavior. However, further efforts are needed to educate students about the specific environmental consequences of textile production, the importance of responsible purchasing, textile recycling, and extending the life cycle of clothing. It is especially important to strengthen the understanding of the relationship between individual consumer habits and the overall negative impact of the textile industry on the environment.

In practical terms, the research results indicate the need to organize educational campaigns, clothing collection and recycling initiatives, as well as to introduce clearer labeling of environmentally friendly textile products. Students, as a young and educated population, can play an important role in raising awareness of sustainable fashion and responsible consumption. However, this requires sufficient information, available sustainable products, and support from educational institutions, manufacturers, and the local community.

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CLOTHING AND ECO LABELS, AND THE DIGITAL PRODUCT PASSPORT: INSIGHTS INTO CONSUMER BEHAVIOUR

Scientific paper
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ABSTRACT: *The fashion and textile industry faces significant environmental challenges. In the transition toward a circular economy, clothing labels and eco-labels play an important role in communicating sustainability information to consumers. To further enhance transparency, the European Union is introducing Digital Product Passports (DPPs), which provide detailed information on product life cycles.*
This study examines Slovenian consumers' perceptions of clothing labels, eco-certifications, and DPPs, as well as their influence on purchasing decisions. A quantitative online survey explored shopping habits, attention to clothing label information, awareness of eco-certifications, and attitudes toward the adoption and use of DPPs. The results show that consumers check clothing labels and express interest in sustainability-related information. Awareness of eco-certifications and DPPs is present but varies across respondents, while attitudes toward digital product information are generally positive, although often neutral. The findings suggest that the DPP has potential to improve transparency and access to product information, depending on consumer awareness and the clarity of information provided.

Keywords: *Clothing labels, Eco labels, Consumer behaviour, Sustainable consumption, Purchasing behaviour, Digital Product Passport (DPP).*

OZNAKE NA ODEĆI, EKOLOŠKE OZNAKE I DIGITALNI PASOŠ PROIZVODA: PERCEPCIJE I PONAŠANJE POTROŠAČA

APSTRAKT: *Modna i tekstilna industrija suočavaju se sa značajnim ekološkim izazovima. U tranziciji ka cirkularnoj ekonomiji, oznake na odeći i ekološke oznake imaju važnu ulogu u prenošenju informacija o održivosti potrošačima. Kako bi se dodatno unapredila transparentnost, Evropska unija uvodi digitalne pasoše proizvoda (Digital Product Passports – DPPs), koji pružaju detaljne informacije o životnom ciklusu proizvoda.*
Ova studija ispituje percepcije slovenskih potrošača o oznakama na odeći, ekološkim sertifikatima i DPP-u, kao i njihov uticaj na odluke o kupovini. Kvantitativno online istraživanje obuhvatilo je navike kupovine, obraćanje pažnje na informacije na oznakama odeće, svest o poznavanju ekoloških sertifikata i stavove prema usvajanju i korišćenju DPP-a. Rezultati pokazuju da potrošači proveravaju oznake na odeći i izražavaju

interesovanje za informacije povezane sa održivošću. Svest o eko-certifikatima i DPP-u je prisutna, ali varira među ispitanicima, dok su stavovi prema digitalnim informacijama o proizvodima uglavnom pozitivni, iako često neutralni. Nalazi ukazuju na to da DPP ima potencijal da poboljša transparentnost i pristup informacijama o proizvodima, u zavisnosti od svesti potrošača i jasnoće ponuđenih informacija.

Ključne reči: *Oznake na odeći, ekološke etikete, ponašanje potrošača, održiva potrošnja, kupovno ponašanje, digitalni pasoš proizvoda (DPP).*

1. INTRODUCTION

The fashion and textile industry represents a significant global sector with considerable economic, environmental, and social impacts. Production and consumption in this industry involve intensive use of natural resources, high energy demand, water pollution, and substantial textile waste. The rise of fast fashion has further accelerated clothing turnover and shortened product lifespans, increasing the overall environmental footprint [1–3]. In response, increasing attention has been directed toward more sustainable production and consumption practices, including improved durability, recyclability, and enhanced supply chain visibility [2, 3].

Clothing labels serve as an important communication tool between producers and consumers, providing key product information such as size, material composition, care instructions, and origin [4]. Beyond their traditional role, clothing labels increasingly incorporate sustainability-related information, such as eco-labels and environmental certifications, as well as information related to environmental and ethical aspects of production and supply chains. However, the effectiveness of such information depends on consumer understanding, trust, and willingness to integrate it into purchase decisions [5-7]. Recent research on Slovenian consumers indicates a generally positive attitude toward eco-friendly textile products, with labels such as “product with certificate” identified as important factors influencing purchase decisions [8]. However, empirical evidence suggests that although eco-labels are recognized, they are not consistently the primary determinant of purchasing decisions, which are often driven by price, quality, and design [5, 9]. Similarly, international studies report that consumer understanding and trust in eco-labels remain limited due to label proliferation, lack of standardisation, and difficulties in interpretation [6, 7, 10]. Consequently, while eco-labels have the potential to encourage sustainable purchasing behaviour, their actual impact is often constrained without clear communication, standardisation, and consumer education [6, 10].

To address these challenges, the European Commission has introduced the EU Strategy for Sustainable and Circular Textiles (COM(2022) 141 final), which includes the implementation of Digital Product Passports (DPPs) [2]. According to the European Parliamentary Research Service, DPPs are expected to enhance traceability, product-level information access, and circularity in the textile value chain by providing digital access to data such as materials, production processes, and lifecycle information [11]. Digital

Product Passports have recently gained increasing attention in EU policy, academic research, and industry practice. Emerging empirical evidence suggests that DPPs may improve consumer confidence and support more sustainable purchasing decisions, although research remains in an early stage [12-14]. Industry perspectives further highlight that DPPs can provide consumers with detailed sustainability-related information, including material origin and environmental impact data, thereby strengthening product-level information accessibility across the product lifecycle [15].
Nevertheless, empirical research on consumer awareness, acceptance, and willingness to use DPPs in the textile sector remains limited. Building on this gap, this study investigates Slovenian consumers' perceptions of clothing labels, eco-certifications, and Digital Product Passports, as well as their influence on purchasing decisions.

2. RESEARCH DESIGN AND METHODOLOGY

This study employed a quantitative research design using a structured online questionnaire to examine Slovenian consumers' perceptions of clothing labels, eco-certifications, and Digital Product Passports (DPPs). The study investigated shopping habits, attention to clothing labels, awareness of eco-labels, and willingness to use DPPs.

Table 1: Demographic characteristics of respondents

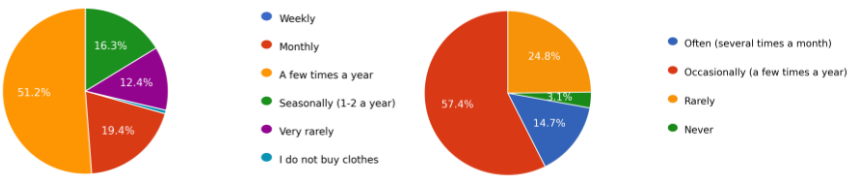
Variable	Category	Frequency	Percent (%)
Gender	Male	12	9.3
	Female	113	87.5
	Other / Prefer not to say	4	3.2
Age	18–25	35	27.1
	26–35	16	12.4
	36–50	43	33.3
	51–65	31	24.0
	65+	4	3.1
Education	Primary / Secondary	0	0
	Vocational / Technical	40	31.0
	University / Higher Education	56	43.4
	Master's / PhD	29	22.5

A convenience sample of Slovenian consumers was recruited through online platforms and social media. No personally identifiable data were collected, and respondents provided informed consent prior to participation. The sample included respondents of different ages, genders, education levels, employment statuses, and regions of residence. A total of 129

respondents participated in the survey. Table 1 presents the demographic characteristics of the respondents.
The questionnaire consisted of four sections: demographics; shopping behaviour (purchase frequency, preferences for sustainable materials, shopping channels, and key purchase factors); clothing labels and eco-information (awareness, understanding, importance, and attitudes towards sustainability-related information measured using a 5-point Likert scale); and Digital Product Passports (awareness, attitudes, and willingness to use). Data were collected over a five-week period (20 March–24 April 2026) through an online survey. After the completion of the survey, the collected data were analysed using descriptive statistical methods, including frequency analyses and cross-tabulations.

3. RESULTS AND DISCUSION

The sample characteristics are presented in Table 1. The sample consisted of 87.5% female and 9.3% male respondents, with the remaining percentage comprising other or non-disclosed categories. The largest age group was 36–50 years (33.3%), followed by respondents aged 18–25 years (27.1%). In terms of education, most respondents had completed university or higher education (43.4%).
The first part of the analysis examined respondents' clothing purchasing habits, including shopping channels, purchase frequency, use of online and second-hand markets, purchases of organic or sustainable clothing, and key purchase decision factors. Figure 1a presents the frequency of clothing purchases among respondents. Most respondents purchased clothing several times per year (51.2%), followed by monthly purchases (19.4%) and seasonal purchases (16.3%). Infrequent purchasing was reported by 12.4% of respondents, while only 0.8% reported purchasing clothing weekly. Overall, the results indicate that clothing purchases are generally occasional rather than frequent.



a) b)

Figure 1: Frequency of clothing purchases:
(a) General clothing purchases and
(b) Purchases of clothing made from organic or other ecological or sustainable materials

Purchases of clothing made from organic or other ecological or sustainable materials
Figure 1b presents the frequency of purchasing clothing made from organic, ecological, or other sustainable materials. Most respondents reported purchasing such garments several times per year (57.4%), followed by rare purchases (24.8%) and frequent purchases, defined as several times per month (14.7%). Only 3.1% reported never purchasing such items. These findings suggest that sustainable clothing is already part of respondents'

purchasing behaviour; however, for most respondents, such purchases remain occasional rather than regular.

Figure 2 presents respondents' clothing purchasing channels (multiple responses allowed). The most frequently used channel is stores selling new clothing (69.8%), followed by online shopping (62.0%). Outlet stores are used by 19.4% of respondents, while 3.1% shop in luxury fashion stores. Second-hand consumption is also present, including physical second-hand stores (41.1%), online second-hand platforms (22.5%), and clothing swap events (9.3%). A small number of respondents reported making or exchanging clothing themselves.

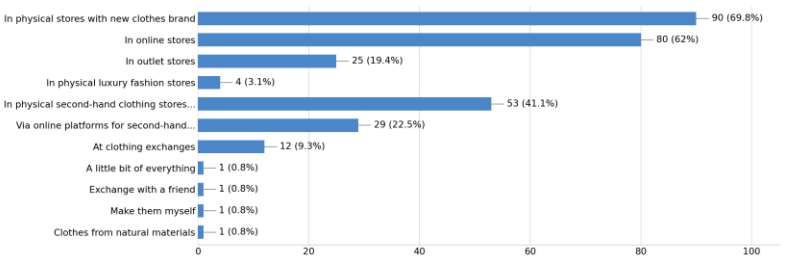
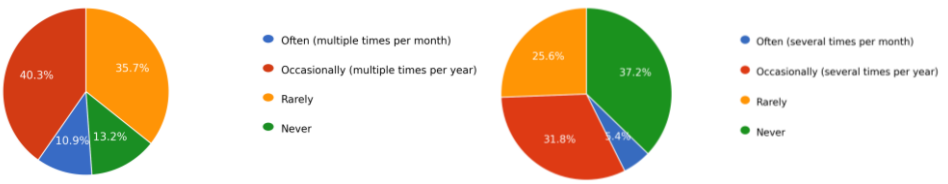


Figure 2: Clothing purchasing channels



a) b)

Figure 3: Frequency of clothing purchases by channel: (a) Online stores and (b) Second-hand stores or online second-hand platforms

Figure 3a shows the frequency of online clothing purchases among respondents. Most respondents purchase clothing online occasionally, defined as several times per year (40.3%), followed by rare purchases (35.7%) and no online purchases (13.2%). Frequent online shopping, defined as several times per month, was reported by 10.9% of respondents. Figure 3b presents the frequency of purchasing second-hand clothing through physical or online platforms. A total of 37.2% of respondents do not engage in second-hand shopping, while 31.8% purchase second-hand clothing occasionally (several times per year), 25.6% do so rarely, and 5.4% purchase second-hand clothing frequently (several times per month). Overall, online clothing shopping is more widespread, while second-hand purchasing is less frequent and includes many non-users.

Figure 4 presents the factors respondents consider most important when purchasing clothing. Material quality and quality of workmanship are the most important factors for 44.2% of respondents, followed by comfort and fit (23.3%). Design, cut, and colour are

prioritised by 18.6%, while price is the key factor for 7.0% of respondents. Sustainability and ecological materials are identified as the primary consideration by 3.9% of respondents. Overall, the results indicate that functional and quality-related aspects are prioritised over price and sustainability in clothing purchase decisions.

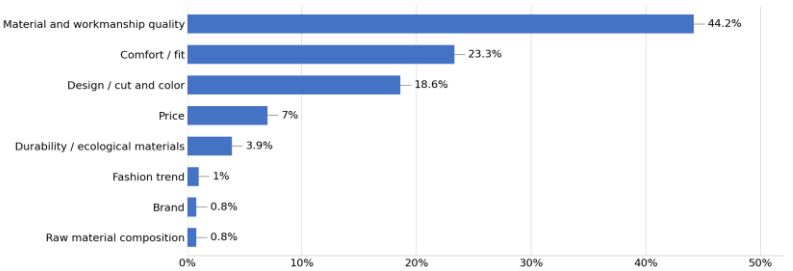


Figure 4: Key factors in clothing purchase decisions

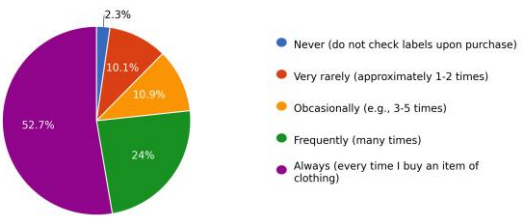


Figure 5: Frequency of checking clothing labels during purchase

The second part of the analysis examines clothing and eco/sustainability labels, including attention to label information, key and missing information, and familiarity with and trust in certifications. Figure 5 presents how often respondents check clothing label information when purchasing garments. Most respondents reported always checking labels (52.7%) or doing so frequently (24.0%), followed by occasional checking (10.9%). Very rare checking was reported by 10.1%, while only 2.3% never check labels. Overall, the results indicate that clothing labels are an important source of information in the purchasing process.

Figure 6a shows the types of information respondents usually read on clothing labels (multiple responses allowed). Fibre composition is the most frequently consulted information (89.9%), followed by size (72.9%) and care instructions (69.8%). Manufacturer and country of production are considered by 44.2% of respondents, while 36.4% pay attention to sustainability information or certifications. Warnings and recommendations (28.7%), additional material information (20.9%), and brand name (17.8%) are selected less frequently. Figure 6b presents the information on clothing labels considered most important in purchase decisions (multiple responses allowed). Material composition is by far the most important factor (93.8%), followed by care instructions (45.0%). Sustainability labels and certifications influence 27.1% of respondents, while 24.0% consider origin and ethical production. Brand name (11.6%) and size (0.8%) are least important.

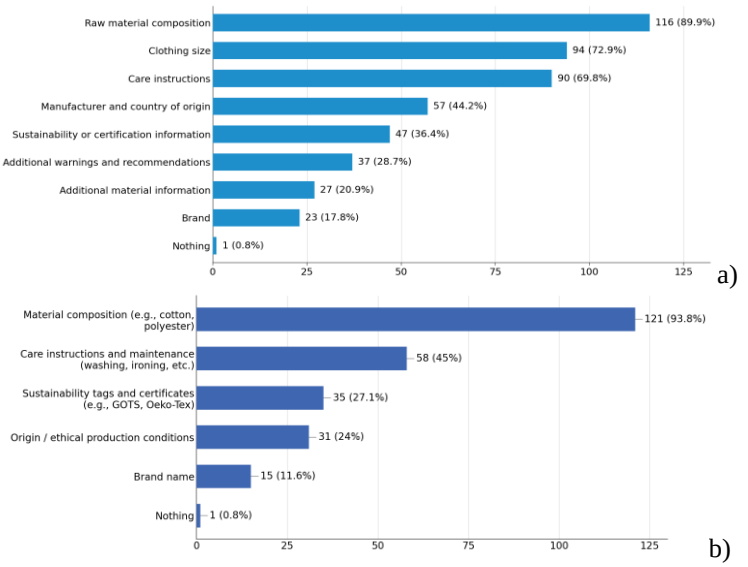
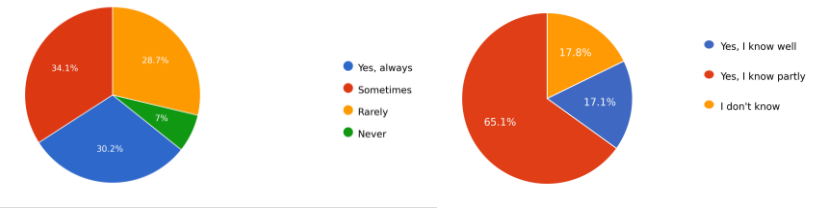


Figure 6: Clothing label information: (a) Information read and (b) Information considered most important

The analysis also examined missing information on clothing labels and label-related discomfort. Most respondents reported a lack of information on ethical production (67.4%), followed by sustainability-related details such as recycled or organic materials and certifications (45.7%), and more detailed material properties, such as wrinkle resistance, water repellence, etc. (39.5%). Additionally, 27.9% indicated that clothing labels should provide more specific care instructions, such as washing garments inside out and air-drying only, etc. Overall, respondents expect more transparent and detailed information regarding sustainability, production practices, material characteristics, and garment care. In addition, 96.9% (125 of 129 respondents) reported removing clothing labels due to discomfort, mainly because of itching (92.9%) and thickness or bulkiness (42.1%). Open-ended responses further highlighted issues such as oversized or poorly placed labels, excessive translations, visibility through lighter fabrics, and too many labels attached to a single garment.

Respondents were asked how often they check whether clothing materials are sustainable, organic, or certified with eco/sustainability labels. As shown in Figure 7a, 34.1% sometimes check this information, 30.2% always do, 28.7% rarely do, and 7.0% never do. Responses indicate a varied level of attention to sustainability-related information in purchasing decisions. Figure 7b presents respondents' familiarity with ecological and sustainability labels. Most respondents (65.1%) report partial familiarity, while 17.1% report good familiarity and 17.8% are not familiar at all.



a) b)

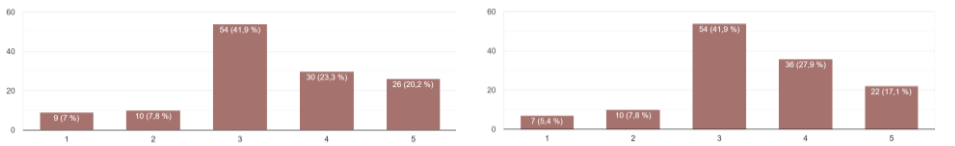
Figure 7: Sustainability information on clothing: (a) Checking information and (b) Familiarity with eco labels

The survey also examined respondents' familiarity with ecological, sustainability, and other clothing-related labels (multiple responses allowed). The most recognized label was OEKO-TEX Standard 100 (68.2%), followed by the EU Ecolabel (58.1%), OEKO-TEX Made in Green (45.7%), and the Global Organic Textile Standard (GOTS) (43.3%). Lower recognition was observed for the Blue Angel (23.3%) and Better Cotton (20.9%), while 10.1% reported no familiarity with any ecological labels. Familiarity with additional sustainability certifications was also assessed. Fair Trade/Fair Wear Foundation was recognized by 57.4% of respondents, followed by the Global Recycled Standard (30.2%), Cradle to Cradle Certified™ (20.9%), and Bluesign® (11.6%). A total of 26.4% were not familiar with any of these certifications.

Respondents were also asked about their level of trust in sustainability labels and ecological certifications on clothing (1 = no trust, 5 = complete trust). Most respondents reported moderate trust (47.3%), followed by high trust (29.5%) and complete trust (10.9%). Lower levels of trust were reported by 8.5%, while 3.9% reported no trust. Overall, trust in sustainability labels is generally positive but cautious. In addition, respondents were asked whether clearer sustainability information and eco-labels would influence their decision to purchase sustainable clothing. The majority indicated that they would probably be influenced (43.4%), followed by those who were unsure (24.8%). A further 22.5% stated that they would be influenced, while 8.5% reported that they would probably not be influenced. Overall, improved clarity and visibility of sustainability information could positively influence consumers' purchasing decisions, although a considerable share of respondents remains uncertain. The study also revealed that consumers express a notable willingness to pay more for garments made from sustainable materials with eco-labels. Specifically, a substantial majority are willing to pay extra for verified eco-friendly products: 39.5% would pay 10–20% more, 18.6% up to 10% more, and 16.3% between 20–30% more. Furthermore, 8.5% indicated they would not pay anything extra, while another 8.5% would be willing to pay 30–50% more, and 5.4% would pay over 50% more.

The next section focused on the Digital Product Passport (DPP) for clothing. Slightly more than half of respondents (55.8%) reported that they were not familiar with the concept, while 44.2% indicated that they had previously heard of the DPP. Respondents most frequently reported having heard about the DPP at events, workshops, or conferences (18.6%) and in the workplace (17.8%). This was followed by websites or news portals

(11.6%) and social media (9.3%). Fewer respondents reported having encountered the concept through education (8.5%), clothing brands (5.4%), or friends and family (3.9%). Furthermore, 34.1% of respondents reported having encountered a QR code on clothing providing product-related information, while 65.9% had not. Despite this limited experience, interest in QR-based digital information is relatively high, as 73.6% indicated that they would scan a QR code if it replaced traditional labels and provided all relevant product information, whereas 26.4% would not. Respondents were also asked about their likelihood of scanning a DPP when purchasing clothing. Most reported that they would be very likely (34.9%) or likely (27.9%) to do so, while 20.2% indicated that they might scan it. A smaller proportion reported that they would be unlikely (11.6%) or very unlikely/not willing (5.4%) to engage with it.



a) b)

Figure 8: Attitudes toward the Digital Product Passport (DPP):
(a) Sustainable purchase decisions and (b) Trust in eco-certifications

Figure 8a presents respondents' attitudes toward the DPP in supporting more sustainable clothing purchase decisions (1 = strongly disagree, 5 = strongly agree). Responses were distributed with a neutral majority (41.9%), followed by agreement (23.3%) and strong agreement (20.2%), while 7.8% disagreed and 7.0% strongly disagreed. Figure 8b presents respondents' perceptions of whether a DPP would increase their trust in eco-certifications and labels on clothing. Responses were similarly distributed, with a neutral majority (41.9%), followed by agreement (27.9%) and strong agreement (17.1%), while 7.8% disagreed and 5.4% strongly disagreed. Respondents were also asked to what extent they agree that information on a DPP would be useful in making purchase decisions (1 = strongly disagree, 5 = strongly agree). Responses showed a neutral majority (34.9%), followed by agreement (34.1%) and strong agreement (20.2%), while 6.2% disagreed and 4.7% strongly disagreed. Overall, across all three statements, responses indicate a general tendency toward agreement, although a substantial proportion of respondents remained neutral.

Respondents were asked which types of information they would like to access digitally via a Digital Product Passport (multiple responses allowed). The most desired information was fibre composition (74.4%), followed by raw material origin (72.1%). A high level of interest was also expressed in care and maintenance information and other material-related data (65.1%), as well as information on production processes and working conditions (62.8%). More than half of respondents indicated interest in material certifications (56.6%), recycling information (53.5%), and full product traceability (52.7%). Lower but still

notable interest was observed for repairability information (45.7%) and the product's carbon footprint (38.8%).

The results indicate substantial interest in several types of digital product information, particularly fibre composition, raw material origin, care and maintenance instructions, and production-related aspects, as these were selected by a large share of respondents. Interest in environmental impact information, such as carbon footprint, was lower in comparison, although still present among a considerable proportion of respondents. In addition, most respondents indicated that DPP information would be useful in their purchasing decisions, and over 60% reported a positive likelihood of using such digital information when available. Overall, the Digital Product Passport is perceived as a potentially useful tool for providing product-related information across multiple dimensions. Its potential influence on consumer decision-making will depend on increasing awareness and ensuring that the information provided is clear, accessible, and relevant to purchasing contexts.

4. CONCLUSION

This study examined Slovenian consumers' clothing purchasing behaviour, attention to clothing labels, awareness of eco-certifications, and perceptions of the Digital Product Passport (DPP). Results show that clothing is purchased at a relatively moderate frequency, primarily several times per year, followed by monthly and seasonal purchases. Purchases are mainly made through physical stores and online platforms, while second-hand clothing purchasing is also present but less frequent. A similar pattern is observed for sustainable clothing, which is mostly purchased occasionally rather than regularly, indicating that sustainability is still not a dominant driver of clothing consumption.

Consumers demonstrate a relatively high level of engagement with clothing labels, most commonly by checking key product information such as fibre composition and care instructions. However, label-related discomfort is highly prevalent, as nearly all respondents reported having removed clothing labels due to irritation (itching), thickness, or bulkiness. This highlights a trade-off between the informational value of labels and their physical usability, as the material form of labels can negatively affect user experience despite their role in providing product-related information.

Awareness of ecological and sustainability labels is present, with most respondents reporting partial familiarity, while a smaller share indicated good familiarity. The highest recognition is observed for certifications such as OEKO-TEX, the EU Ecolabel, and the Global Organic Textile Standard (GOTS). Respondents also report varying levels of attention to sustainability-related information in clothing materials, with most indicating that they occasionally check whether materials are sustainable, organic, or certified, suggesting that such considerations are present but not consistently integrated into purchasing decisions. Trust in sustainability labels is generally positive but cautious, reflecting acceptance without strong confidence. At the same time, respondents express expectations for more comprehensive information, particularly regarding sustainability, material properties, and detailed garment care instructions. Overall, awareness of

sustainability labels and material-related sustainability information is present, while their use in decision-making remains inconsistent.

Regarding digital product information, awareness of the Digital Product Passport (DPP) remains limited, although a considerable share of respondents has encountered the concept, mainly through professional and formal information channels. Only a minority of respondents reported having scanned QR codes on clothing providing product-related information, indicating that the current implementation of digital product information in the clothing sector remains limited. Despite this, consumers show generally positive attitudes toward digital product information and express willingness to engage with it when available.

The findings indicate substantial interest in detailed digital product information, particularly regarding material composition, raw material origin, care and maintenance instructions, production processes, and working conditions. Sustainability-related information, including certifications, recycling information, and product traceability, is also valued. Although interest in carbon footprint and repairability information is somewhat lower, these aspects are still relevant for a considerable share of respondents. Respondents also perceive DPP information as useful in their purchasing decisions, supporting its relevance in consumer decision-making. Taken together, the results suggest that although sustainability is not yet the primary driver of clothing purchases, there is a clear demand for improved information availability and greater transparency. The Digital Product Passport represents a relevant development in this direction, but its impact will depend on effective implementation and integration into everyday consumer decision-making.

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FROM DENIM TO SUSTAINABLE ALTERNATIVES: STUDENTS' AWARENESS OF ENVIRONMENTAL IMPACTS AND THEIR ACCEPTANCE OF DENIM-LOOK PANTS

Scientific paper
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ABSTRACT: *The environmental impacts of conventional denim production, including intensive water and energy consumption, extensive chemical use, and wastewater generation, have increased interest in more sustainable alternatives. This study investigated textile and fashion students' awareness of these impacts and evaluated their acceptance of a sustainable denim-look garment developed through an industry–university collaboration. A qualitative research design was adopted involving nine female undergraduate students. Data were collected through semi-structured interviews before and after a 15-day wear trial of the developed trousers. The results showed that participants' environmental awareness was generally limited to excessive water consumption. Although attitudes toward sustainable fashion were positive, purchasing decisions remained primarily influenced by aesthetics, comfort, quality, and price. After the wear trial, the garment received highly positive evaluations for its visual similarity to conventional denim, comfort, breathability, and overall usability, with only minor suggestions regarding colour tone and fabric handle. The findings suggest that combining sustainability education with direct product experience can enhance sustainability-oriented design thinking and increase acceptance of environmentally responsible textile products.*

Keywords: *sustainable denim; denim-look garment; environmental awareness; sustainable fashion; user experience.*

OD TEKSASA DO ODRŽIVIH ALTERNATIVA: SVEST STUDENATA O EKOLOŠKIM UTICAJIMA I NJIHOVO PRIHVATANJE PANTALONA SA IZGLEDOM TEKSASA

APSTRAKT: *Uticaji konvencionalne proizvodnje teksasa na životnu sredinu, uključujući intenzivnu potrošnju vode i energije, ekstenzivnu upotrebu hemikalija i stvaranje otpadnih*

voda, povećali su interesovanje za održivije alternative. Ova studija je istraživala svest studenata tekstilne i modne industrije o ovim uticajima i procenila njihovo prihvatanje održivog odevnog predmeta sa izgledom teksasa razvijenog kroz saradnju između industrije i univerziteta. Usvojen je kvalitativni istraživački dizajn koji je obuhvatio devet studentkinja osnovnih studija. Podaci su prikupljeni putem polustrukturiranih intervjua pre i posle 15-dnevnog probnog nošenja razvijenih pantalona. Rezultati su pokazali da je ekološka svest učesnika uglavnom bila ograničena na prekomernu potrošnju vode. Iako su stavovi prema održivoj modi bili pozitivni, odluke o kupovini su i dalje prvenstveno uticale estetika, udobnost, kvalitet i cena. Nakon probnog nošenja, odevni predmet je dobio veoma pozitivne ocene zbog svoje vizuelne sličnosti sa konvencionalnim teksasom, udobnosti, prozračnosti i ukupne upotrebljivosti, sa samo manjim sugestijama u vezi sa tonom boje i opterećenjem tkanine. Rezultati sugerišu da kombinovanje obrazovanja o održivosti sa direktnim iskustvom sa proizvodom može poboljšati dizajnersko razmišljanje orijentisano na održivost i povećati prihvatanje ekološki odgovornih tekstilnih proizvoda.

Ključne reči: *održivi teksas; odevni predmet sa izgledom teksasa; ekološka svest; održiva moda; korisničko iskustvo.*

1. INTRODUCTION

The fashion industry is one of the world’s largest consumer-driven sectors, generating substantial economic value while creating significant environmental and social challenges. The shift from seasonal production to fast fashion has led to shorter product life cycles, rapid turnover, and increasing consumption. Global clothing sales nearly doubled from approximately USD 1 trillion in 2002 to USD 1.8 trillion in 2015, illustrating the expansion of apparel consumption and overconsumption [1]. Growing environmental concerns have made sustainability a strategic priority, accelerating the adoption of circular economy principles that promote resource efficiency, waste reduction, and sustainable production and consumption [2]. At the same time, globalization and complex supply chains have increased demands for transparent sustainability reporting and responsible production [3]. Initiatives such as the Green Carpet Fashion Awards and the Sustainable Apparel Coalition encourage sustainable materials, circular design, ethical production, and standardized environmental performance assessment [4]–[6]. Despite these initiatives, the fashion industry remains largely dependent on a linear production model based on virgin materials, resulting in intensive resource consumption and waste generation. This has also intensified concerns about greenwashing, emphasizing the need for transparent and verifiable sustainability claims [7], [8]. Accordingly, recent studies highlight that meaningful sustainability requires a transition from fast fashion to circular production systems and responsible consumption across the fashion value chain [10], [15]–[18]. Within this context, educating future fashion designers is essential for supporting sustainable transformation. This study aims to increase students’ awareness of the environmental impacts of conventional denim production and promote sustainability-oriented design thinking. Through an industry–university collaboration, a sustainable denim-look garment

was introduced as an alternative to conventional denim trousers, and students' perceptions of the product were evaluated to encourage sustainability-oriented material selection, product development, and design decision-making.

2. DENIM PRODUCTION AND ENVIRONMENTAL IMPACTS

According to the United Nations Environment Programme (UNEP), achieving sustainability in the textile value chain requires a systemic transformation of production, consumption, and circular infrastructure, as incremental improvements alone are insufficient to address the sector's environmental challenges [14]. Likewise, the Pulse Score (2018) reported that the fashion industry achieved only 38 out of 100 in sustainability performance, despite improvements in resource efficiency [15]. As a result, the industry continues to face major challenges, including textile waste, excessive water and chemical use, microfiber pollution, poor labour conditions, child labour, and greenwashing, increasing pressure for transparent and circular production systems [11]–[13]. Denim, originally developed as workwear, has become one of the world's most widely consumed textile products because of its durability and versatility. However, its environmental impacts extend across the entire life cycle, from cotton cultivation and indigo dyeing to garment manufacturing, transportation, and consumer use. Despite these impacts, global demand continues to grow. North America accounted for 31.2% of global denim revenue in 2024, while Europe and the Asia–Pacific region are projected to grow at CAGR rates of 6.0% and 7.0%, respectively, between 2025 and 2030 [19]. Growing consumer interest in sustainability has encouraged the adoption of recycled fibres, organic cotton, low-impact dyeing, and water-efficient finishing technologies. Nevertheless, conventional denim production remains highly resource intensive. Therefore, current research focuses on developing sustainable alternatives that preserve denim's appearance, comfort, durability, and consumer acceptance while reducing environmental impacts, including denim-look fabrics, regenerated cellulosic fibres, recycled materials, and other circular textile solutions [19]. Environmental impacts occur throughout the denim life cycle, from cotton cultivation to consumer use, with dyeing and finishing representing the most resource-intensive stages. Consequently, reducing the environmental footprint of denim production through cleaner technologies and circular strategies has become a major sustainability priority [20].

Water consumption is a major environmental challenge because cotton cultivation and wet processing require large volumes of freshwater, while textile production contributes approximately 20% of global water pollution. Denim wastewater contains dyes and processing chemicals, encouraging the adoption of water-saving technologies such as laser finishing, ozone treatment, foam dyeing, and water recycling systems [20]–[22]. Conventional denim production also depends on intensive chemical and energy use. Therefore, enzymatic treatments, bio-based chemicals, renewable energy, waste heat recovery, and process optimization have become key strategies for reducing environmental impacts [20]–[23]. In addition, greenhouse gas emissions from yarn, fabric, and wet processing highlight the need for integrated sustainability strategies across the denim supply chain [22].

Denim-look fabrics have emerged as sustainable alternatives that replicate the appearance of woven denim while reducing environmental impacts. Circular knitted structures, digital printing, engineered jacquard fabrics, and innovative finishing technologies enable authentic denim aesthetics with substantially lower water and chemical consumption. These fabrics increasingly incorporate recycled cotton, regenerated cellulosic fibres, recycled polyester, and elastane to improve environmental performance. The development of sustainable denim has also promoted the use of recycled cotton, organic cotton, hemp, and regenerated cellulosic fibres such as lyocell [24]. Recycled cotton reduces the demand for virgin resources, while regenerated cellulose fibres and recycled polyester support circular material flows [24]–[26]. Hemp requires less irrigation and fewer agrochemicals than cotton, whereas lyocell offers a closed-loop production process, biodegradability, effective moisture management, and favourable mechanical properties, making both fibres promising alternatives for sustainable denim applications [25], [27].

3. YOUNG CONSUMERS' ENVIRONMENTAL AWARENESS AND SUSTAINABLE FASHION ATTITUDES

Generation Z, born between the mid-1990s and early 2010s, is a key consumer group shaping the future of the fashion industry. Growing up in a digitally connected environment, they increasingly consider sustainability, transparency, and ethical production alongside price, quality, and style when making purchasing decisions, encouraging brands to adopt more sustainable production practices. Although environmental awareness has increased demand for recycled materials, circular design, repair services, and second-hand markets, purchasing decisions remain strongly influenced by comfort, aesthetics, quality, price, and brand reputation. Reducing this gap requires consumer education together with affordable, attractive, and genuinely sustainable products. User experience is a key factor influencing the acceptance of sustainable denim. Besides environmental performance, consumers evaluate comfort, fit, appearance, durability, quality, and similarity to conventional denim, while price, brand reputation, product availability, and trust in sustainability claims also affect purchasing decisions. Environmental awareness alone does not ensure sustainable purchasing behaviour. Consumers are more likely to adopt sustainable denim alternatives when they provide aesthetics, comfort, quality, and functionality comparable to conventional products. Therefore, successful market adoption depends on both improved environmental performance and positive user experiences supported by effective sustainability communication [28]–[31]. Accordingly, this study investigates consumers' perceptions, user experiences, and purchase intentions regarding denim-look trousers developed as an environmentally friendly alternative to conventional denim.

4. MATERIALS AND METHODS

4.1 Research Design

The study was conducted in three phases; First, a denim-look garment was designed and produced to replicate the appearance of conventional denim while avoiding resource-

intensive manufacturing processes. Second, participants wore the garment during a controlled wear trial. Finally, semi-structured interviews explored their experiences, perceptions of comfort, aesthetics, sustainability, and purchase intentions. This sequential approach enabled participants to evaluate the product through direct use, generating richer qualitative data. It adopted a qualitative product evaluation design integrating sustainable product development, wear trials, and user experience assessment. Rather than relying solely on interviews, the research combined the development of an environmentally friendly denim-look garment with user-centred evaluation to investigate participants' environmental awareness and perceptions of a sustainable alternative to conventional denim.

4.2 Production of the Denim-Look Trousers

The trousers were manufactured from a two-thread knitted cotton fabric engineered to resemble woven indigo denim, with the denim appearance achieved through digital printing (Fig.1-4). Cotton production is associated with intensive water use and the extensive application of pesticides and fertilizers, creating significant environmental concerns [25]. This study addresses the use of denim-look fabrics as a sustainable alternative to conventional denim.

Figure 1: (left) Model1-(17194D-ZR-467-V1)**Figure 2:** (right) Model2- (17186D-ZR-03-V1)

Figure 3: (left) Model3-(17188D-ZR-05-V1) **Figure 4:** (right) Model4- (17187D-ZR-04-V1)

Model #1 (17194D-ZR-467-V1): To minimise the influence of fashion style on participants' evaluations, the first prototype adopted a familiar five-pocket jeans construction with a waistband, belt loops, back yoke, fly opening, and decorative topstitching. Digital printing reproduced washed indigo effects, subtle fading, and twill-like textures without conventional dyeing, washing, or finishing processes. A regular-fit, straight-leg silhouette preserved the visual identity of traditional denim while providing everyday comfort, enabling evaluation of a sustainable alternative with authentic denim aesthetics.

Model #2 (17186D-ZR-03-V1): The second prototype was developed as a straight-leg distressed denim-look trouser retaining the essential construction details of conventional jeans. Digitally printed stonewashed effects, whiskering, abrasion marks, and distressed details recreated the appearance of aged denim through twill-like textures and tonal colour variations without mechanical abrasion or chemical washing.

Model #3 (17188D-ZR-05-V1): The third prototype featured a dark indigo denim-look design with a classic straight-leg silhouette and the characteristic construction details of conventional jeans. A deep indigo base combined with digitally printed fading, abrasion effects, and twill textures reproduced authentic denim while creating a cleaner, premium appearance. The design demonstrated how digital printing can replicate conventional denim aesthetics without resource-intensive dyeing, washing, or abrasion processes.

Model #4 (17187D-ZR-04-V1): The fourth prototype was designed as a stonewashed denim-look trouser with a classic straight-leg silhouette and the standard construction details of conventional jeans. A medium-to-dark indigo palette with digitally printed stonewashed effects, localized fading, whiskering, distressed details, and twill textures recreated the appearance of naturally aged denim. The design successfully combined aesthetic and functional requirements while reproducing the visual characteristics of conventional denim through appropriate fabric structure, colour, surface texture, and garment details.

Among four digitally developed alternatives, Model 4 was selected for production because it most closely resembled authentic denim. The design was digitally printed onto transfer paper using a Konica Minolta textile printing system and applied to the fabric by heat-transfer printing, providing high-quality image reproduction while reducing water, chemical, and wastewater consumption compared with conventional denim finishing (Fig.5-8).

The digitally printed fabric was cut and sewn into a complete garment. The addition of a zipper and metal button created a waistband and overall appearance closely matching that of conventional denim jeans (Fig.5-8). After printing, each pattern piece was cut through energy-efficient laser processing and assembled using conventional sewing techniques. Laser cutting enhances sustainability by minimizing fabric waste through precise nesting optimization, reducing consumable use with contact-free cutting, improving production accuracy to decrease rework, enabling on-demand and customized manufacturing to reduce overproduction, and supporting seamless integration into automated digital production systems. The remaining unprinted white fabric offcuts were sufficiently clean and homogeneous to remain suitable for further use. The garment required only a zipper and a single metal button as additional components. Decorative rivets and eyelets were reproduced through digital printing rather than attached as metal hardware, substantially reducing the metal content of the garment. This approach also preferred to improve recyclability, as metal accessories such as rivets, buttons,

and zippers are recognised as factors that complicate textile recycling and material recovery in denim products.

4.3. Participants and Wear Trial Procedure

The second phase consisted of a controlled wear trial in which participants examined and wore the developed garment. The study group consisted of 11 female university students enrolled in different academic departments at various universities who voluntarily agreed to participate in the research. A purposive sampling strategy, specifically criterion sampling, was employed to recruit the participants. Purposive sampling enables researchers to obtain rich and in-depth information from relatively small samples by selecting participants who are particularly relevant to the research objectives [32]. According to Yıldırım and Şimşek (2011), criterion sampling involves selecting all cases that meet a set of predetermined criteria established either by the researcher or by previously defined standards [33]. Accordingly, three inclusion criteria were established for participation in the study: (i) being currently enrolled as a university student and (ii) having previous experience in purchasing and wearing denim trousers (iii) having basic knowledge of textiles, garment construction, or fashion products, enabling them to evaluate the developed garment from both functional and aesthetic perspectives. These criteria ensured that all participants were familiar with conventional denim products and were therefore capable of providing informed evaluations of the alternative garment developed within the scope of this research. Participation was voluntary, and informed consent was obtained prior to data collection.

Figure 5 (left): Printing process by Konika Minolta **Figure 6 (right):** Two-thread fleece

Figure 7 (left): Wist band and zipper closure **Figure8 (right):** Manufactured pants

4.4. Wear Trial and User Experience Evaluation

Participants first received a brief explanation of the environmental impacts of conventional denim production and the sustainability objectives of the developed garment. They then examined and wore the denim-look trousers under identical conditions, evaluating their appearance, denim similarity, comfort, fit, flexibility, freedom of movement, and overall quality. Immediately after the trial, semi-structured interviews were conducted to record participants' initial impressions and user experiences.

Figure 9: Wear trials

4.5. Data Collection Procedure

Data were collected in two consecutive phases using semi-structured interviews. In the first phase, participants completed interviews addressing **Theme 1** (Awareness of the Environmental Impacts of Denim Production) and **Theme 2** (Attitudes Toward Sustainable Fashion and Environmental Responsibility), focusing on their environmental awareness, sustainability perceptions, and clothing consumption behaviours before product exposure. Participants then wore the developed denim-look trousers under normal daily conditions for 15 days. After the wear trial, a second round of interviews explored **Theme 3** (Evaluation of the Denim-Look Alternative Product), examining aesthetic and functional evaluations, user experiences, and perceptions of the garment as an alternative to conventional denim. Conducting interviews after the wear trial ensured that the findings reflected actual user experience and enhanced the ecological validity of the study. Data were collected through face-to-face semi-structured interviews comprising open-ended questions covering five dimensions: environmental awareness, aesthetic perception, perceived comfort, sustainability evaluation, and purchase intention. Each interview lasted approximately 10–15 minutes. Nine participants completed both interview rounds, and their interviews were transcribed verbatim.

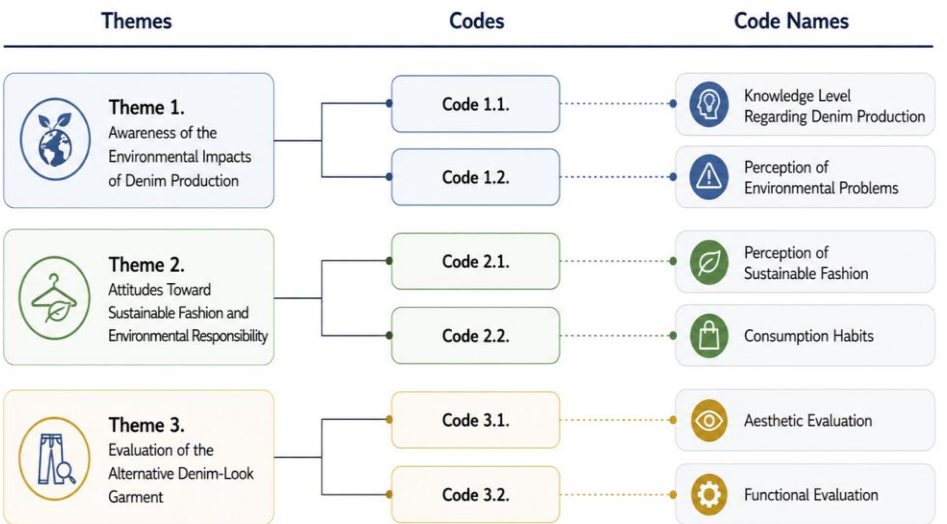

Figure 10: Thematic framework of the study

4.6. Data Analysis

The interview transcripts were analysed using thematic analysis. Meaningful statements were coded and grouped into categories and themes using an inductive approach. The findings were interpreted based on participants' actual wear experiences, enhancing the credibility and ecological validity of the study.

5. RESULTS AND DISCUSSION

The findings present participants' evaluations of the developed denim-look garment regarding aesthetics, comfort, sustainability, and purchase intention, based on their experiences following the 15-day wear trial.

5.1. Theme1: Awareness of the Environmental Impacts of Denim Production

Code 1.1. Knowledge Level Regarding Denim Production

Participants demonstrated a basic awareness of the environmental impacts of denim production, although their knowledge was mainly limited to excessive water consumption. Most identified high water use (f = 7), while fewer mentioned chemical use (f = 2), energy consumption (f = 2), or environmental pollution (f = 3). Two participants reported little or no prior knowledge. Water-intensive processes were most frequently identified as the stage causing the greatest environmental impact (f = 5), followed by stone washing and finishing (f = 2) and dyeing (f = 1), while two participants could not identify a specific stage. University education was the primary information source (f = 6), followed by social and digital media (f = 4). Overall, awareness existed but remained largely restricted to water consumption.

Code 1.2. Perception of Environmental Problems

Participants regarded denim production as environmentally burdensome, mainly because of excessive water use (f = 6), and several emphasized the need for more sustainable production methods (f = 3). Two participants suggested replacing conventional denim with environmentally friendly alternatives. Chemicals and production waste were widely recognized as environmental and health risks (f = 6), although many participants admitted limited knowledge of the chemicals involved (f = 4). Stone washing was identified as one of the most harmful processes (f = 2). All participants agreed that public awareness of denim's environmental impacts is insufficient (f = 9) and believed that greater awareness could encourage more sustainable production and consumption. Overall, participants associated denim production primarily with water use and chemical pollution, while demonstrating limited understanding of broader environmental issues.

5.2. Theme 2. Attitudes Toward Sustainable Fashion and Environmental Responsibility

Code 2.1. Perception of Sustainable Fashion

Participants generally expressed positive attitudes toward sustainable fashion, although the level of understanding varied. Sustainable fashion was most frequently associated with environmentally responsible production and consumption (f = 4) and ethical production and resource conservation (f = 4). Some referred to recyclable materials and circular production (f = 2), while others emphasized durability and long product life (f = 3). Only one participant associated sustainability mainly with recycled fabrics (f = 1).

Most participants reported considering environmental factors when purchasing clothing (f = 6), and several intentionally preferred durable products or reduced denim consumption (f = 4). However, two participants prioritized design, price, and quality over environmental concerns (f = 2). Attitudes toward sustainable textile products were unanimously positive (f = 9); participants described them as beneficial for the environment and human health (f = 5), supported wider adoption (f = 3), and one participant noted that sustainability labels could influence purchasing decisions (f = 1). Overall, favourable attitudes did not always translate into purchasing behaviour.

Code 2.2. Consumption Habits

Purchasing decisions were mainly driven by quality (f = 5), comfort (f = 5), price (f = 5), and fabric characteristics (f = 6), whereas sustainability-related attributes were mentioned less frequently (f = 4). Colour (f = 2), design (f = 1), and product labels (f = 1) had relatively little influence. Most participants were willing to pay more for environmentally friendly products (f = 8), provided they also offered good quality, durability, comfort, or reasonable pricing (f = 5), while one participant remained uncertain (f = 1). Aesthetics was the primary purchasing criterion for most participants (f = 5), four preferred products combining aesthetics and sustainability (f = 4), and only one prioritized sustainability (f = 1). Overall, sustainability complemented rather than replaced conventional purchasing criteria.

5.3. Theme 3. Evaluation of the Denim-Look Alternative Product

Code 3.1. Aesthetic Evaluation

Participants evaluated the denim-look garment positively and considered it visually similar to authentic denim. Most described it as visually successful (f = 6), and several stated that it was difficult to distinguish from real denim (f = 4). Others appreciated its environmentally friendly concept (f = 4) and comfort (f = 3), although a few noted the absence of the rigid structure and tactile feel of conventional denim (f = 2). Most participants agreed that the garment successfully replicated authentic denim (f = 7), while suggesting minor improvements in colour tone (f = 3) and printed pocket details (f = 1). The realistic texture, colour, washing effects, stitching, and overall appearance were the most appreciated visual characteristics (f = 6). Overall, participants considered the garment an aesthetically successful sustainable alternative, requiring only minor refinements.

Code 3.2. Functional Evaluation

Participants reported a high level of acceptance, particularly because of the garment's comfort and flexibility. Most expressed willingness to wear it regularly (f = 8), emphasizing its softness and comfort (f = 5), while some suggested minor design improvements (f = 3). Comfort, flexibility, and freedom of movement were the most expected performance characteristics (f = 7), and lightweight structure and breathability were also valued (f = 4). Several participants considered the garment more comfortable than conventional denim because it avoided stiffness and heat discomfort (f = 4). Most believed it could successfully replace conventional denim in daily use (f = 8). Although some noted that it did not fully replicate denim's rigid handle (f = 4), they still regarded it as a practical alternative because of its superior comfort, recommending only minor structural or visual improvements (f = 3). Overall, the denim-look garment was considered a comfortable and practical alternative with high user acceptance.

6. CONCLUSIONS

The findings indicate that although future textile and fashion designers are aware of the environmental impacts of conventional denim production, their knowledge is largely limited to water consumption, highlighting the need for broader sustainability education covering textile production and circular design principles. Although participants expressed positive attitudes toward sustainable fashion, purchasing decisions remained primarily influenced by aesthetics, quality, comfort, and price. A key contribution of this study is the evaluation of a sustainable denim-look garment developed through an industry–university collaboration. Produced using digital printing instead of conventional indigo dyeing and washing processes, the garment reduced water, chemical, and energy consumption while maintaining the appearance of traditional denim. Participants evaluated the product positively, particularly for its visual similarity, comfort, and flexibility, with only minor suggestions regarding colour, fabric handle, and structure. Overall, the findings suggest that combining sustainability education with direct product experience can strengthen sustainability-oriented design thinking and increase acceptance of environmentally

responsible textile products, especially when sustainability is combined with attractive design, comfort, and functional performance.

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IMPULSIVE CLOTHING PURCHASING AMONG YOUNG CONSUMERS IN SHTIP, NORTH MACEDONIA: IMPLICATIONS FOR SUSTAINABLE FASHION AND ENVIRONMENTAL AWARENESS

Scientific paper
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ABSTRACT: *This study investigates the phenomenon of impulsive clothing purchasing among young consumers in Štip, North Macedonia, and examines its implications for sustainability and environmental awareness. Data were collected through a structured questionnaire based on a five-point Likert scale administered to 45 respondents of different social status (pupils, students, employed, and unemployed), with additional demographic information gathered on gender and age. The collected data were analyzed using descriptive statistical methods and percentage analysis. The findings indicate that impulsive clothing purchasing is a widespread behavior among young people. The highest tendency toward impulsive buying was observed among female respondents and the youngest age groups (under 18 and 18–24 years), whereas male respondents and older participants demonstrated greater restraint in their purchasing behavior. These results reveal a gap between awareness of sustainable consumption and actual consumer behavior, highlighting the continued influence of fashion trends, social pressure, and fast-fashion practices on young consumers. The study concludes that although young people are particularly susceptible to impulsive clothing purchases, they also represent the group with the greatest potential to adopt sustainable consumption practices. Therefore, educational initiatives, awareness campaigns, and policies promoting sustainable fashion should primarily target younger consumers in order to encourage responsible purchasing behavior and contribute to long-term environmental sustainability.*

Keywords: *impulsive buying; sustainable fashion; consumer behavior; environmental awareness; young consumers.*

IMPULSIVNA KUPOVINA ODEĆE MEĐU MLADIMA U ŠTIPU, SEVERNA MAKEDONIJA: IMPLIKACIJE ZA ODRŽIVU MODU I EKOLOŠKU SVEST

APSTRAKT: *Cilj ovog istraživanja bio je da se analizira fenomen impulsivne kupovine odeće među mladima i njegove implikacije na održivost i ekološku svest. Anketa je sprovedena putem upitnika sa pitanjima formulisanim na Likertovoj skali, među 45 ispitanika različitog statusa (učenici, studenti, zaposleni i nezaposleni), uz prikupljanje dodatnih demografskih podataka o polu i starosti. Podaci su obrađeni deskriptivnim statističkim metodama i procentualnom analizom. Rezultati pokazuju da je impulsivna kupovina široko rasprostranjen fenomen među mladima, pri čemu su žene i najmlađe starosne grupe (ispod 18 i 18–24 godine) najsklonije ovakvom ponašanju, dok muškarci i stariji ispitanici pokazuju veću uzdržanost. Ova ambivalentnost naglašava potrebu za edukativnim programima i kampanjama koje promovišu održivu modu i razvoj svesnih potrošačkih navika. Zaključak ukazuje da je mlada generacija istovremeno najpodložnija impulsivnoj potrošnji i najotvorenija za promene ka održivim praksama, što je čini kritičnom ciljnom grupom za buduća istraživanja i intervencije usmerene ka izgradnji kulture održivosti i ekološke odgovornosti.*

Ključne reči: *impulsivna kupovina; održiva moda; potrošačko ponašanje; ekološka svest; mladi potrošači.*

1. INTRODUCTION

Impulsive clothing purchasing among young consumers has become an increasingly significant phenomenon in modern consumer society, driven by the rapid expansion of **fast fashion**, digital marketing, and social media [1,2]. The continuous availability of inexpensive clothing, combined with aggressive promotional strategies and the influence of online platforms, encourages frequent purchasing behavior that often exceeds consumers' actual needs. Consequently, clothing consumption has evolved beyond fulfilling functional requirements and has become closely associated with self-expression, social identity, and lifestyle [3].

Psychological theories suggest that impulsive buying is strongly influenced by emotional regulation, the desire for immediate gratification, and the pursuit of self-esteem and social acceptance [4]. At the same time, social factors including peer influence, fashion trends, celebrity endorsements, and digital influencers reinforce impulsive purchasing behavior, particularly among young consumers, who are more susceptible to external influences and rapidly changing market trends [5].

From the perspective of sustainable development, these consumption patterns raise important environmental concerns. The fast-fashion industry is recognized as one of the largest contributors to textile waste, excessive resource consumption, and environmental pollution [2,6,7]. As Fletcher [1] argues, sustainable fashion is not only concerned with environmentally responsible production but also with transforming consumer attitudes and purchasing behavior. Although young people generally demonstrate a relatively high level of awareness regarding environmental issues and sustainable consumption, numerous studies indicate a persistent gap between environmental awareness and actual purchasing behavior [1,3,8,9]. This contradiction reflects the complexity of consumer decision-

making, where environmental responsibility often competes with emotional impulses, fashion trends, affordability, and social expectations.
Despite the growing body of research on sustainable fashion and consumer behavior, relatively limited attention has been paid to impulsive clothing purchasing among young consumers in **North Macedonia** [3,4,10]. Understanding the purchasing habits of this population is essential for developing effective educational initiatives and sustainability strategies aimed at encouraging responsible consumption and reducing the environmental impact of the textile and fashion industries [11-16].
Therefore, the aim of this study is to examine the prevalence of impulsive clothing purchasing among young people in Štip, North Macedonia, and to analyze how gender and age influence purchasing behavior. Furthermore, the study seeks to highlight the relationship between impulsive consumption and sustainable fashion, emphasizing the importance of environmental awareness and responsible consumer behavior among younger generations.

2. MATERIALS AND METHODS

The study employed a quantitative research design based on a structured questionnaire to investigate young consumers' attitudes toward impulsive clothing purchasing and its relationship with sustainability and environmental awareness. The questionnaire consisted of statements evaluated using a five-point Likert scale**,** ranging from 1 ("strongly disagree") to 5 ("strongly agree")**.** In addition to the attitude statements, demographic information regarding gender, age, and respondents' status (pupils, students, employed, and unemployed) was collected to enable comparative analysis across different groups.
The survey included 45 respondents from Štip, North Macedonia, representing different educational and employment backgrounds. Although the sample size was relatively small, it provided a diverse representation of the target population and offered valuable insights into the purchasing behavior of young consumers. The questionnaire was administered anonymously in order to ensure the confidentiality of participants and encourage honest responses, thereby improving the reliability of the collected data.
The collected data were analyzed using descriptive statistical methods, with percentage analysis employed to determine the distribution of responses for each survey statement. Comparative analyses were subsequently conducted according to gender and age to identify potential differences in impulsive clothing purchasing behavior among demographic groups. This analytical approach enabled a clear interpretation of the findings and facilitated the identification of consumer behavior patterns associated with impulsive purchasing and sustainable consumption.

3. RESULTS AND DISCUSSION

This section presents the findings obtained from the survey conducted among young consumers in Štip, North Macedonia. The results provide insights into respondents' attitudes toward impulsive clothing purchasing and reveal differences according to gender

and age. The graphical analysis not only illustrates the level of agreement with the statement that young people often purchase clothing without a genuine need but also identifies behavioral patterns that have important implications for sustainable consumption and environmental responsibility.

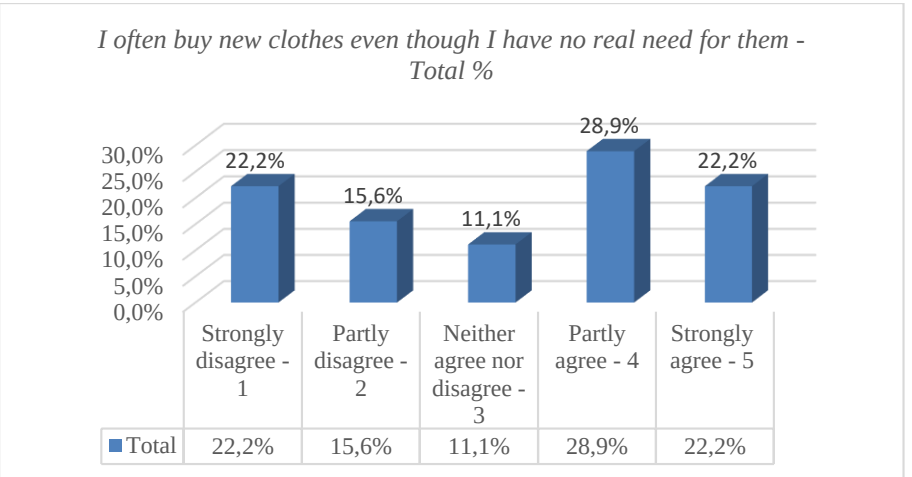


Figure 1: Distribution of responses regarding impulsive clothing purchasing

Figure 1 illustrates the overall distribution of responses to the statement, *"I often buy new clothes even though I have no real need for them."* The largest proportion of respondents (28.9%) partly agreed, while 22.2% strongly agreed, indicating that more than half of the respondents acknowledged engaging in impulsive clothing purchasing to some extent. Conversely, 22.2% strongly disagreed and 15.6% partly disagreed, suggesting that a considerable proportion of young consumers consciously regulate their purchasing behavior. A relatively small percentage of respondents (11.1%) expressed a neutral opinion.

These findings suggest that impulsive clothing purchasing is a common behavioral pattern among young consumers. The coexistence of agreement and disagreement indicates that although many respondents recognize their tendency toward impulsive buying, others demonstrate greater self-control and awareness of responsible consumption. This ambivalence reflects the ongoing conflict between consumer culture and sustainable purchasing practices. This finding is consistent with previous studies reporting that young consumers frequently experience a conflict between fashion-oriented consumption and sustainable purchasing behavior [1,3].

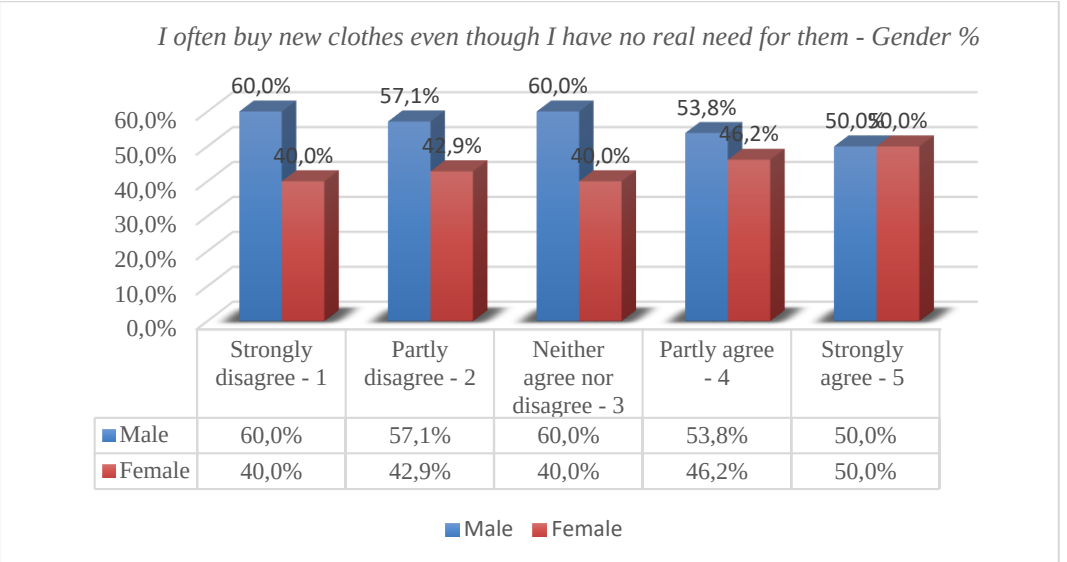
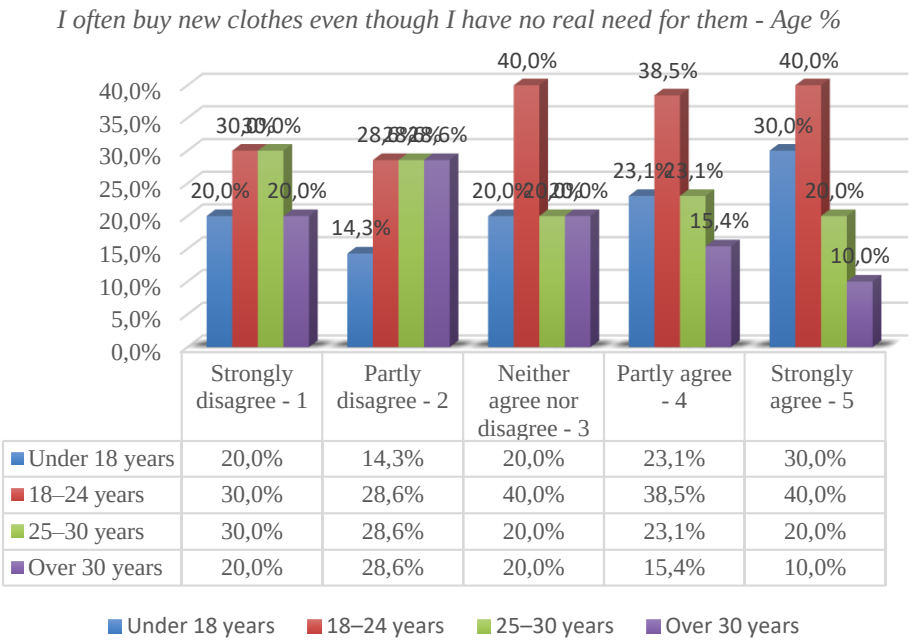


Figure 2: Distribution of responses by gender

Figure 2 presents the distribution of responses according to gender. Male respondents predominantly expressed disagreement with the statement, with 60% strongly disagreeing and 57.1% partly disagreeing, indicating a lower tendency toward impulsive clothing purchasing. Female respondents, in contrast, demonstrated higher levels of agreement, particularly within the categories partly agree and strongly agree, where their responses were more evenly distributed.

These results suggest that female respondents may be more susceptible to impulsive clothing purchasing than male respondents. Similar gender-related differences have been reported in previous studies of consumer behavior and impulsive buying [4,5]. This difference may be associated with social and cultural influences, including greater exposure to fashion trends, social media marketing, and appearance-related expectations reported in previous studies [5]. However, because the present study did not investigate the underlying causes of purchasing behavior, these findings should be interpreted cautiously and viewed as possible explanations rather than definitive causal relationships.



	Strongly disagree - 1	Partly disagree - 2	Neither agree nor disagree - 3	Partly agree - 4	Strongly agree - 5
Under 18 years	20,0%	14,3%	20,0%	23,1%	30,0%
18–24 years	30,0%	28,6%	40,0%	38,5%	40,0%
25–30 years	30,0%	28,6%	20,0%	23,1%	20,0%
Over 30 years	20,0%	28,6%	20,0%	15,4%	10,0%

Figure 3: Distribution of responses by age

Figure 3 illustrates the distribution of responses across different age groups. The highest levels of agreement were observed among respondents under 18 years of age and those aged 18–24 years, with 30% and 40%, respectively, strongly agreeing that they often purchase clothing without real necessity. These findings indicate that the youngest respondents demonstrate the greatest tendency toward impulsive buying.

In contrast, respondents aged 25–30 years displayed a more balanced distribution of responses, while participants over 30 years of age predominantly disagreed with the statement, suggesting greater purchasing restraint and more rational consumer behavior.

The observed age differences may reflect increasing consumer experience, financial responsibility, and environmental awareness that develop over time. Younger consumers are generally more exposed to digital marketing, social media, influencer culture, and rapidly changing fashion trends, all of which encourage impulsive purchasing behavior [3,5]. These findings emphasize the importance of educational initiatives promoting sustainable fashion and responsible consumption, particularly among younger age groups [6,7].

Overall, the results demonstrate that impulsive clothing purchasing is a widespread phenomenon among young consumers, particularly among female respondents and the youngest age groups. Although many participants recognize the importance of responsible consumption, their purchasing behavior continues to be strongly influenced by fashion

trends and consumer culture. This discrepancy between environmental awareness and actual consumer behavior has also been identified in previous research on sustainable fashion and consumer decision-making [1,3]. Educational programs, awareness campaigns, and initiatives encouraging conscious purchasing habits are essential for reducing excessive clothing consumption and its associated environmental impacts.

4. CONCLUSION

The findings of this study confirm that impulsive clothing purchasing is a widespread behavior among young consumers**,** with significant differences observed according to gender and age. Female respondents and the youngest age groups (under 18 and 18–24 years) demonstrated the highest tendency toward impulsive purchasing, whereas male respondents and older participants exhibited greater restraint and more rational purchasing behavior. These findings indicate that demographic characteristics play an important role in shaping consumer habits and purchasing decisions.

The study further highlights the contradiction between young people's awareness of environmental issues and their actual purchasing behavior. Although many respondents recognize the importance of sustainable consumption, their purchasing decisions continue to be strongly influenced by fashion trends, social media, and consumer culture [3]. This gap between environmental awareness and consumer behavior demonstrates that promoting sustainability requires not only increasing knowledge but also encouraging long-term changes in consumer attitudes and purchasing habits.

The findings contribute to a better understanding of impulsive clothing purchasing among young consumers in North Macedonia by identifying demographic groups that are particularly vulnerable to impulsive consumption [4]. From a practical perspective, the results suggest that educational programs, sustainability campaigns, and initiatives promoting responsible fashion consumption should primarily target younger consumers, especially adolescents and young adults, in order to encourage more conscious purchasing behavior and reduce the environmental impact of the fashion industry.

This study is limited by the relatively small sample size and its focus on respondents from a single city, which restricts the generalizability of the findings. Future research should include larger and more geographically diverse samples, as well as investigate additional factors influencing impulsive clothing purchasing, such as income level, social media use, fashion involvement, and environmental values.

In conclusion, encouraging responsible clothing consumption among young people represents an important step toward reducing textile waste, promoting sustainable fashion, and supporting the transition to a more environmentally responsible society. Developing consumer awareness together with practical sustainable purchasing habits will contribute not only to environmental protection but also to the establishment of a long-term culture of sustainable consumption.

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A CONCEPTUAL CAM-5 FRAMEWORK FOR CIRCULAR ADDITIVE MANUFACTURING IN ENGINEERING AND TEXTILE APPLICATIONS

Scientific paper
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ABSTRACT: *The growing demand for sustainable manufacturing has accelerated the adoption of circular economy (CE) principles across engineering and industrial sectors. Among advanced manufacturing technologies, additive manufacturing (AM) has emerged as a key enabler of sustainable production due to its ability to minimize material waste, optimize resource utilization, support product customization, and facilitate decentralized manufacturing. Simultaneously, both engineering and textile industries are undergoing a transition toward circular production systems driven by increasing environmental concerns, resource efficiency requirements, and digital transformation. This paper presents a critical review of the role of circular economy principles in additive manufacturing, with particular emphasis on sustainable engineering and textile applications. The study analyzes the integration of circular economy strategies throughout the additive manufacturing lifecycle, including sustainable material selection, digital product design and simulation, resource-efficient manufacturing, circular product lifecycle management, and recycling within closed-loop manufacturing systems. Current opportunities, technological challenges, and future research directions are also discussed to provide a comprehensive overview of recent developments in this rapidly evolving field. Based on the findings obtained from the literature review, the authors propose the CAM-5 (Circular Additive Manufacturing – Five Pillars) conceptual framework, which integrates five complementary pillars for implementing circular economy principles in additive manufacturing: Sustainable Materials, Digital Design & Simulation, Resource-Efficient Additive Manufacturing, Circular Product Lifecycle, and Recycling & Closed-Loop Manufacturing. The proposed framework provides a systematic perspective for integrating sustainability principles into additive manufacturing while demonstrating its potential contribution to engineering and textile applications. The proposed CAM-5 framework may serve as a conceptual foundation for future research focused on sustainability assessment, industrial case studies, and the practical implementation of circular manufacturing strategies within engineering and textile production systems.*

Keywords: *Additive manufacturing; Circular economy; Sustainable manufacturing; CAM-5 framework; Sustainable engineering; Textile industry.*

KONCEPTUALNI CAM-5 OKVIR ZA CIRKULARNU ADITIVNU PROIZVODNJU U INŽENJERSKIM I TEKSTILNIM PRIMENAMA

APSTRAKT: *Sve veća potreba za održivom proizvodnjom ubrzala je primenu principa cirkularne ekonomije (CE) u inženjerskim i industrijskim sektorima. Među savremenim proizvodnim tehnologijama, aditivna proizvodnja (AM) izdvojila se kao jedan od ključnih pokretača održive proizvodnje zahvaljujući mogućnosti smanjenja otpada materijala, optimizacije korišćenja resursa, podrške prilagođenoj proizvodnji i decentralizovanih proizvodnih procesa. Istovremeno, inženjerska i tekstilna industrija prolaze kroz tranziciju ka cirkularnim proizvodnim sistemima, podstaknutu rastućim ekološkim zahtevima, potrebom za efikasnijim korišćenjem resursa i procesima digitalne transformacije. U ovom radu prikazan je kritički pregled uloge principa cirkularne ekonomije u aditivnoj proizvodnji, sa posebnim osvrtom na održive primene u inženjerstvu i tekstilnoj industriji. Analizirana je integracija strategija cirkularne ekonomije kroz celokupan životni ciklus aditivne proizvodnje, uključujući izbor održivih materijala, digitalno projektovanje i simulaciju proizvoda, resursno efikasnu proizvodnju, upravljanje cirkularnim životnim ciklusom proizvoda i reciklažu u okviru zatvorenih proizvodnih sistema. Takođe su razmotrene aktuelne mogućnosti, tehnološki izazovi i budući pravci istraživanja kako bi se pružio sveobuhvatan pregled savremenih dostignuća u ovoj brzo razvijajućoj oblasti. Na osnovu rezultata pregleda literature, autori predlažu konceptualni okvir CAM-5 (Circular Additive Manufacturing – Five Pillars), koji integriše pet komplementarnih stubova za primenu principa cirkularne ekonomije u aditivnoj proizvodnji: održivi materijali, digitalno projektovanje i simulacija, resursno efikasna aditivna proizvodnja, cirkularni životni ciklus proizvoda i reciklaža u okviru zatvorenih proizvodnih sistema. Predloženi okvir pruža sistematski pristup integraciji principa održivosti u aditivnu proizvodnju, istovremeno ukazujući na njen potencijal za primenu u inženjerstvu i tekstilnoj industriji. Predloženi CAM-5 okvir može predstavljati konceptualnu osnovu za buduća istraživanja usmerena na procenu održivosti, industrijske studije slučaja i praktičnu primenu strategija cirkularne proizvodnje u inženjerskim i tekstilnim proizvodnim sistemima.*

Ključne reči: *Aditivna proizvodnja; Cirkularna ekonomija; Održiva proizvodnja; CAM-5 okvir; Održivo inženjerstvo; Tekstilna industrija.*

1. INTRODUCTION

The transition towards sustainable manufacturing has become one of the main priorities of modern industry due to increasing environmental concerns, resource depletion, climate

change, and stricter environmental regulations. Manufacturing companies are expected to reduce their environmental footprint while maintaining productivity, product quality, and economic competitiveness. As a result, the concept of the circular economy (CE) has gained significant attention as an alternative to the traditional linear production model, promoting the efficient use of resources, waste minimization, material recovery, and product life-cycle extension [1,7,10]. Unlike previous review studies that primarily discuss circular economy principles or additive manufacturing independently, this paper integrates these concepts within a unified perspective applicable to both engineering and textile industries. Furthermore, the study proposes the CAM-5 conceptual framework as a systematic representation of the key pillars supporting circular additive manufacturing.

Unlike conventional manufacturing systems based on the "take–make–dispose" approach, circular economy principles encourage the continuous circulation of materials and products through strategies such as reducing material consumption, reusing components, repairing products, remanufacturing, and recycling end-of-life materials. The implementation of these strategies contributes not only to environmental protection but also to improved resource efficiency, lower production costs, and increased industrial resilience [3,4].

Among emerging manufacturing technologies, additive manufacturing (AM) has been recognized as one of the key enablers of sustainable production. By producing components layer by layer directly from digital models, additive manufacturing significantly reduces material waste compared with conventional subtractive manufacturing processes. In addition, AM supports decentralized production, rapid prototyping, product customization, spare-part manufacturing, and the utilization of recycled or bio-based materials, making it an important technology within circular manufacturing systems [5,6,8,11].

In parallel, the textile industry is undergoing a profound transformation driven by sustainability requirements, circular economy policies, and digital manufacturing technologies. The sector is facing increasing pressure to reduce textile waste, improve material efficiency, decrease energy and water consumption, and adopt environmentally responsible production practices. Consequently, innovative manufacturing technologies, including additive manufacturing, are attracting growing interest for their potential to support sustainable product development, customized textile accessories, wearable products, rapid tooling, spare parts for textile equipment, and engineering solutions integrated into textile production systems [4,12].

Although additive manufacturing and textile production represent different industrial domains, they share common objectives related to sustainable manufacturing, efficient resource utilization, digitalization, and circular material management. Additive manufacturing should therefore be viewed not as a replacement for conventional textile production, but as a complementary technology capable of supporting the development of more flexible, sustainable, and resource-efficient engineering and textile manufacturing systems.

The aim of this paper is to review recent developments related to circular economy strategies in additive manufacturing and to discuss their contribution to sustainable engineering and textile applications. Particular attention is given to material efficiency, circular design principles, recycling opportunities, sustainable materials, and future

directions that may facilitate the integration of circular economy concepts into advanced manufacturing systems.

2. CIRCULAR ECONOMY AS A FOUNDATION FOR SUSTAINABLE MANUFACTURING

2.1. Circular Economy Principles

The circular economy has evolved into one of the most influential frameworks for achieving sustainable industrial development by promoting the continuous use of materials, products, and resources throughout their life cycle. Unlike the traditional linear economy, which relies on extracting raw materials, manufacturing products, and disposing of them after use, the circular economy aims to preserve the value of materials for as long as possible while minimizing waste generation and environmental impacts [7,10].

The implementation of circular economy principles is commonly based on value-retention strategies that seek to extend product life, reduce dependence on virgin resources, and improve resource efficiency. While different frameworks have been proposed in the literature, manufacturing systems frequently adopt the 4R concept, consisting of Reduce, Reuse, Recycle, and Recover, as a practical approach for implementing circular manufacturing strategies. In additive manufacturing, these principles are directly associated with material optimization, product redesign, remanufacturing, polymer recycling, and energy recovery, making the 4R framework particularly suitable for evaluating sustainability performance.

- Reduce focuses on minimizing raw material consumption, production waste, and energy use through optimized product design and manufacturing processes.
- Reuse aims to extend the service life of products and components by enabling repeated use with minimal additional processing.
- Recycle involves converting end-of-life materials into secondary raw materials that can be reintroduced into new manufacturing processes.
- Recover refers to extracting value from materials that cannot be reused or recycled, primarily through energy recovery or other recovery technologies.

Recent studies emphasize that successful implementation of circular economy principles requires more than material recycling alone. Effective circular manufacturing integrates product design, digital technologies, reverse logistics, remanufacturing, and lifecycle management into a comprehensive production strategy. Consequently, circular economy should be considered a systemic transformation of manufacturing rather than a collection of isolated environmental practices.

Table 1: Overview of the 4R principles in sustainable manufacturing

Principle	Objective	Example in Additive Manufacturing	Potential Textile Application
Reduce	Minimize material and energy consumption	Optimized part design, lightweight structures	Material-efficient product design

Reuse	Extend product life	Reuse of tooling and fixtures	Reusable textile accessories
Recycle	Return materials into production	Recycled PLA/PETG filaments	Recycled textile-polymer composites
Recover	Recover value from waste	Energy recovery from polymer waste	Recovery of textile production waste

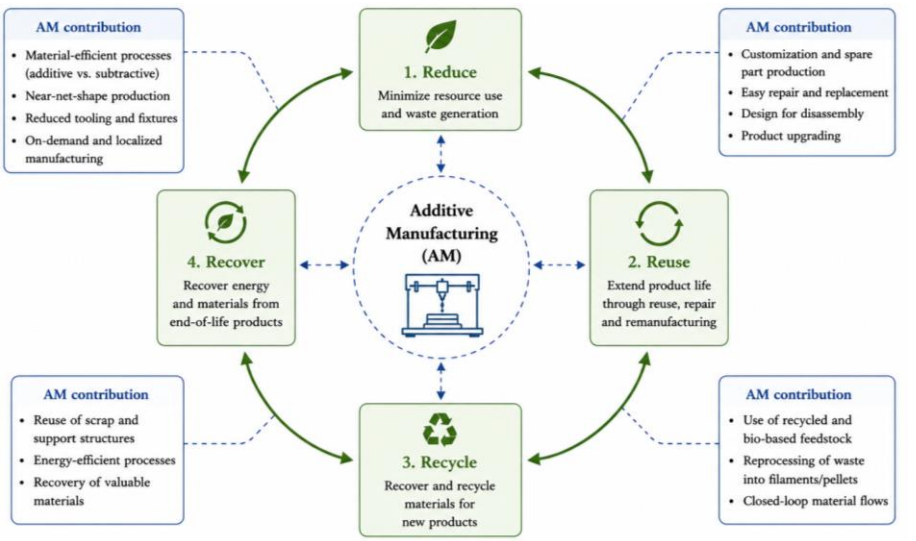

Figure 1: Relationship between the 4R principles of the circular economy and the contribution of additive manufacturing to sustainable resource management

3. ADDITIVE MANUFACTURING AS AN ENABLER OF THE CIRCULAR ECONOMY

Additive manufacturing has become one of the most promising technologies supporting the transition towards circular manufacturing systems. Unlike conventional subtractive manufacturing, where a significant portion of raw material is removed during machining operations, additive manufacturing fabricates components layer by layer, allowing material to be deposited only where required. This manufacturing approach contributes to improved material utilization, reduced waste generation, and greater production flexibility [5, 6, 8].
One of the major advantages of additive manufacturing from a circular economy perspective is its ability to support localized and on-demand production. Manufacturing products close to the point of use reduces transportation requirements, inventory levels, and associated carbon emissions. Furthermore, digital manufacturing enables rapid design modifications and production without additional tooling, thereby extending product functionality while minimizing unnecessary resource consumption [9,11].

Material circularity represents another important aspect of additive manufacturing. Recent advances in polymer processing have enabled the production of recycled and bio-based filaments suitable for FDM technologies. Materials such as recycled PLA, recycled PETG, recycled ABS, and bio-derived polymers contribute to reducing dependence on virgin raw materials while promoting closed-loop material cycles. However, maintaining consistent mechanical performance and process stability remains one of the primary challenges associated with recycled feedstock materials [2,5].

In addition to material efficiency, additive manufacturing facilitates product repair, redesign, and remanufacturing. Instead of replacing entire products, damaged components can be reproduced individually, extending product life and reducing waste generation. This capability is particularly important for engineering industries, where spare parts often become unavailable after product discontinuation, as well as for textile manufacturing systems requiring customized tooling or replacement components.

Digitalization further strengthens the contribution of additive manufacturing to circular economy implementation. Computer-aided design, topology optimization, simulation tools, and digital inventories reduce unnecessary physical stock while enabling rapid product customization and decentralized manufacturing. Consequently, additive manufacturing is increasingly recognized as a key enabling technology supporting Industry 4.0 and Industry 5.0 concepts within sustainable production systems.

Despite these advantages, several challenges still limit the large-scale implementation of circular economy principles in additive manufacturing. These include limited availability of standardized recycled materials, variability in feedstock quality, energy consumption during printing, insufficient recycling infrastructure, and the absence of internationally accepted sustainability assessment methodologies. Addressing these challenges will be essential for achieving fully circular additive manufacturing systems in future industrial applications.

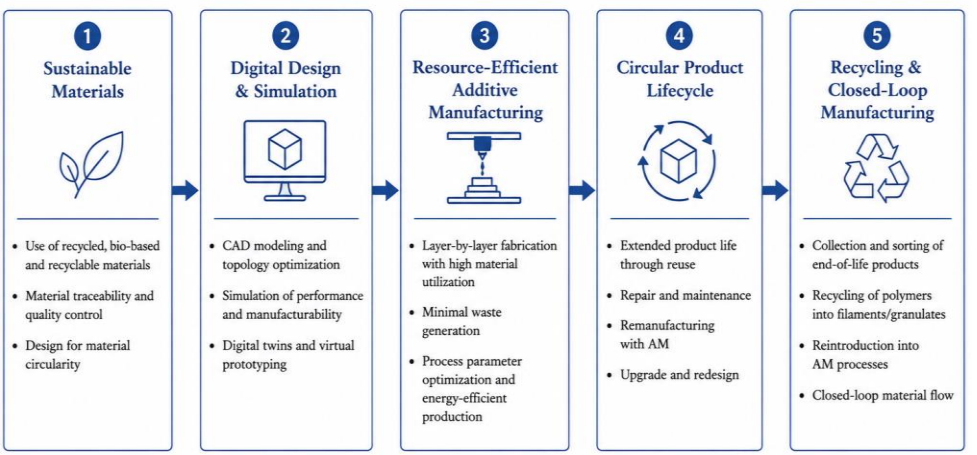

Figure 2: Key sustainability stages through which additive manufacturing supports circular economy implementation

4. ENGINEERING AND TEXTILE APPLICATIONS OF CIRCULAR ADDITIVE MANUFACTURING

The implementation of circular economy principles through additive manufacturing has expanded rapidly across various engineering disciplines, offering innovative solutions for sustainable product development, resource optimization, and waste reduction. Owing to its flexibility, digital workflow, and efficient material utilization, additive manufacturing is increasingly recognized as a valuable production technology capable of supporting both engineering and textile industries in their transition towards more sustainable manufacturing systems [4,8].

4.1 Engineering Applications

Within engineering industries, additive manufacturing enables the production of lightweight structures, functional prototypes, customized products, tooling, molds, and spare parts with considerably lower material waste than conventional manufacturing processes. The possibility of manufacturing components on demand contributes to shorter supply chains, reduced inventory requirements, and lower transportation-related emissions. Moreover, topology optimization and digital design techniques allow engineers to minimize material consumption while maintaining the required mechanical performance, thereby supporting circular economy objectives [5,11]. Another important contribution of additive manufacturing is the repair and remanufacturing of engineering components. Instead of replacing complete assemblies, damaged parts can be reproduced individually, extending product life cycles and reducing the demand for new raw materials. Such practices align closely with circular economy strategies focused on value retention and resource efficiency.

4.2 Textile Applications

The textile industry is increasingly exploring additive manufacturing as a complementary technology rather than a replacement for conventional textile production. Applications include customized textile accessories, garment fasteners, buttons, buckles, wearable products, smart textiles, rapid prototyping, and the production of spare parts for textile machinery. Additive manufacturing also enables greater product personalization and supports small-batch production, which is becoming increasingly important in modern textile markets characterized by rapidly changing consumer demands [11].

From a sustainability perspective, additive manufacturing contributes to reducing production waste and improving material efficiency in textile-related applications. The adoption of recycled polymers and bio-based materials further supports the development of environmentally responsible products while promoting circular material flows. Furthermore, digital production allows manufacturers to produce components only when required, reducing overproduction and inventory, which are among the major sustainability challenges in the textile sector.

The integration of additive manufacturing with digital design, sustainable materials, and circular economy principles demonstrates considerable potential for supporting future

engineering and textile production systems. As Industry 5.0 concepts continue to evolve, collaboration between advanced manufacturing technologies and sustainable product development is expected to play an increasingly important role in achieving environmentally responsible industrial growth.

Table 2: Potential applications of additive manufacturing supporting circular economy principles

Circular strategy	Engineering applications	Textile applications
Reduce	Lightweight components	Optimized product design
Reuse	Repair of spare parts	Reusable accessories
Recycle	Recycled polymer filaments	Recycled textile-polymer products
Recover	Material recovery	Textile waste valorization

5. PROPOSED CAM-5 CONCEPTUAL FRAMEWORK FOR CIRCULAR ADDITIVE MANUFACTURING

The reviewed literature demonstrates that circular economy implementation in additive manufacturing extends beyond material recycling and requires a comprehensive approach that considers the entire product life cycle. Although numerous studies discuss sustainability, material efficiency, and digital manufacturing independently, limited attention has been given to integrating these concepts into a unified framework applicable to both engineering and textile industries.

The proposed CAM-5 framework consists of five interconnected pillars that collectively represent the essential elements required for implementing circular economy principles within additive manufacturing systems. Rather than describing a sequential manufacturing process, the framework emphasizes the integration of complementary sustainability dimensions that should be considered simultaneously throughout the product life cycle. Based on the findings obtained from the reviewed literature, the authors propose the CAM-5 conceptual framework (Figure 3), which integrates five complementary pillars supporting circular additive manufacturing [2,5,7].

The first pillar, sustainable material selection, focuses on choosing environmentally responsible materials, including recyclable polymers, recycled feedstock, and bio-based materials. Material selection directly affects the environmental impact of manufacturing and determines the potential for future material recovery and recycling.

The second pillar involves digital design and product optimization. Modern computer-aided design (CAD), simulation tools, and topology optimization techniques enable the development of lightweight and material-efficient products before manufacturing begins. This approach minimizes unnecessary material consumption while maintaining the required product functionality.

The third pillar represents the additive manufacturing process, where components are fabricated using layer-by-layer deposition. Compared with conventional manufacturing processes, additive manufacturing provides improved material utilization, reduced waste generation, rapid product customization, and decentralized production, thereby supporting several circular economy objectives simultaneously.

Following product utilization, the framework incorporates reuse, repair, and remanufacturing strategies. Instead of replacing complete products, damaged or obsolete components can be repaired or reproduced individually using additive manufacturing technologies. This significantly extends product service life while reducing demand for virgin raw materials.

The fifth pillar includes recycling and material recovery, where end-of-life polymer materials are reprocessed into secondary feedstock suitable for new manufacturing cycles. The continuous implementation of these activities establishes a closed-loop manufacturing system capable of improving resource efficiency and reducing environmental impacts.

The proposed CAM-5 conceptual framework demonstrates that successful implementation of circular economy principles cannot rely on material recycling alone. Instead, sustainable additive manufacturing requires the integration of five complementary pillars encompassing sustainable materials, digital product development, resource-efficient production, circular product life-cycle management, and recycling strategies. Although conceptual in nature, the proposed framework may serve as a foundation for future research, industrial implementation, and sustainability assessment within engineering and textile manufacturing systems.

Unlike existing circular economy frameworks, CAM-5 integrates sustainability principles specifically from the perspective of additive manufacturing while simultaneously considering engineering and textile applications.

Table 3: Comparison between conventional manufacturing and circular additive manufacturing

Aspect	Conventional Manufacturing	Circular Additive Manufacturing
Material use	High waste	Optimized material utilization
Production	Mass production	On-demand production
Repair	Limited	Easy repair/remanufacturing
Recycling	End-of-life	Closed-loop recycling
Sustainability	Linear	Circular

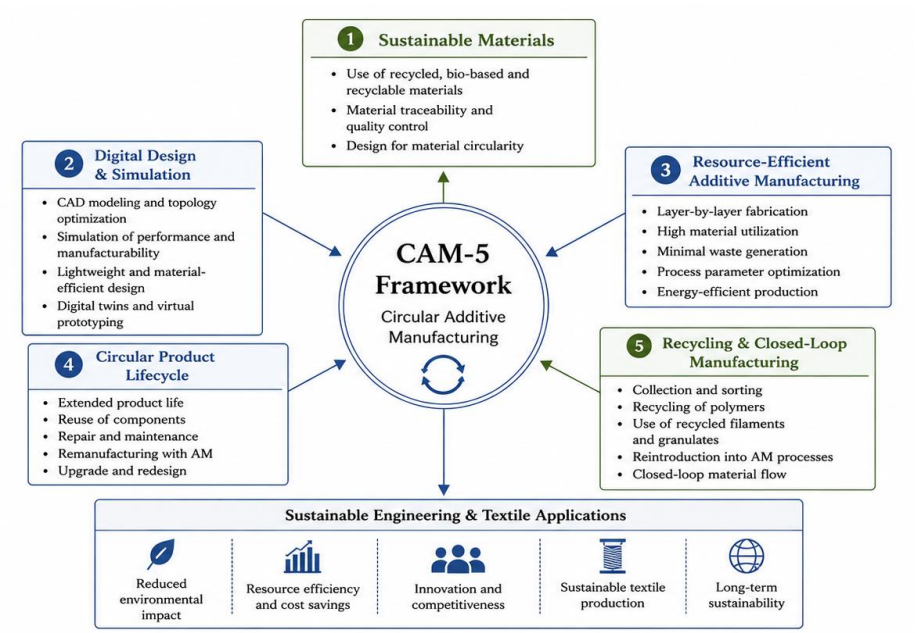

Figure 3: The proposed CAM-5 conceptual framework for integrating circular economy principles into additive manufacturing for sustainable engineering and textile applications (developed by the authors)

6. FUTURE RESEARCH DIRECTIONS

The transition toward sustainable manufacturing requires continuous development of innovative technologies and integrated management strategies that support circular economy implementation. Although additive manufacturing has demonstrated considerable potential for improving material efficiency and reducing production waste, several technological and organizational challenges remain before fully circular manufacturing systems can be achieved [5,7].

One of the most promising research directions involves the development of advanced sustainable materials. Future investigations should focus on improving the quality, mechanical performance, and recyclability of recycled polymer feedstock while expanding the application of bio-based and biodegradable materials suitable for additive manufacturing processes [2,8]. Material traceability and certification systems will also become increasingly important for ensuring reliable circular material flows.

Digitalization is expected to play an essential role in the evolution of circular manufacturing systems. The integration of digital twins, artificial intelligence, machine learning, and real-time process monitoring can significantly improve process optimization,

predictive maintenance, material utilization, and decision-making throughout the manufacturing life cycle. These technologies are closely aligned with the principles of Industry 5.0, which emphasizes sustainable, resilient, and human-centered production systems [4].

Another important research direction concerns the development of comprehensive sustainability assessment methodologies. Future studies should combine environmental, economic, and technical performance indicators to evaluate additive manufacturing processes more objectively. Approaches such as Life Cycle Assessment (LCA), Life Cycle Costing (LCC) (Finnveden et al., 2009), and multi-criteria decision-making (MCDM) methods, including AHP, TOPSIS, and PROMETHEE, may provide valuable tools for selecting sustainable materials and manufacturing strategies [13].

Furthermore, greater collaboration between engineering and textile industries is expected to accelerate the implementation of circular manufacturing principles. The increasing use of recycled materials, customized production, smart textiles, wearable technologies, and digital manufacturing creates new opportunities for integrating additive manufacturing into sustainable textile production systems [12].

Finally, future research should focus on validating the proposed CAM-5 conceptual framework through industrial case studies, comparative sustainability assessments, and practical implementation within manufacturing environments [5,7]. Such validation would enable further refinement of the framework and support its application as a decision-support tool for sustainable engineering and textile manufacturing.

The proposed framework may also serve as a foundation for future quantitative studies aimed at evaluating circular manufacturing performance through sustainability indicators and decision-support methodologies.

7. CONCLUSION

The transition from linear production models toward circular manufacturing systems has become one of the key priorities for achieving sustainable industrial development. This paper reviewed the fundamental principles of the circular economy and discussed the contribution of additive manufacturing to improving material efficiency, reducing production waste, extending product life cycles, and promoting resource recovery. The analysis confirms that additive manufacturing represents an important enabling technology for supporting circular economy implementation in both engineering and textile-related applications.

The findings indicate that additive manufacturing contributes to sustainability through optimized material utilization, decentralized and on-demand production, product customization, and the increasing use of recycled and bio-based materials. These characteristics enable manufacturers to reduce environmental impacts while simultaneously improving production flexibility and resource efficiency.

The review also highlights that engineering, and textile industries share common sustainability objectives despite representing different manufacturing sectors. Circular economy strategies, supported by digital manufacturing technologies, provide new

opportunities for reducing waste generation, improving product life-cycle management, and promoting environmentally responsible production practices. Consequently, additive manufacturing should be considered a complementary technology capable of supporting the transition toward more sustainable manufacturing systems.

As the main contribution of this study, the authors proposed the CAM-5 conceptual framework, which integrates five complementary pillars for implementing circular economy principles in additive manufacturing: sustainable materials, digital design and simulation, resource-efficient additive manufacturing, circular product lifecycle, and recycling with closed-loop manufacturing. The proposed framework provides a systematic perspective that may facilitate future integration of sustainability principles into engineering and textile manufacturing systems.

Although the proposed framework is conceptual in nature, it establishes a foundation for future research focused on its practical validation through industrial case studies, sustainability assessment methodologies, and decision-support approaches. Further investigations may also explore the integration of Industry 5.0 technologies, artificial intelligence, digital twins, and life-cycle assessment methods to enhance the sustainability of additive manufacturing processes and strengthen circular manufacturing strategies.

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GREEN PHOTOCATALYSIS FOR TREATMENT OF DYE POLLUTED WATER

Scientific paper
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ABSTRACT: *The increasing contamination of aquatic environments with a wide range of organic pollutants has highlighted the need for the development and implementation of advanced oxidation processes (AOPs). Among these, photocatalysis has attracted considerable attention due to its high degradation efficiency and environmental compatibility, despite certain inherent limitations. Therefore, continuous efforts to enhance both the efficiency and sustainability of photocatalytic systems remain a major focus of current research in water treatment technologies. In this study, synthesized* TiO_2 *was employed as a photocatalyst for the degradation of methyl violet dye in aqueous solution. The effect of the initial photocatalyst dosage on the degradation efficiency was systematically investigated. The experimental results demonstrated that the optimal photocatalytic performance was achieved using a* TiO_2 *concentration of 0.20 g/L for an initial dye concentration of 10 mg/L. These findings contribute to a better understanding of photocatalytic processes and provide valuable insights for the development of efficient treatment strategies for textile wastewater.*

Keywords: *water treatment, photodegradation,* TiO_2*, organic pollutants.*

ZELENA FOTOKATALIZA U PREČIŠĆAVANJU VODA ZAGAĐENIH BOJOM

APSTRAKT:*Sve izraženije zagađenje vodenih ekosistema širokim spektrom organskih polutanata ukazalo je na potrebu za razvojem i primenom unapređenih oksidacionih*

procesa (AOP). Među njima, fotokataliza zauzima značajno mesto zahvaljujući visokoj efikasnosti razgradnje organskih zagađujućih materija i ekološkoj prihvatljivosti, uprkos određenim ograničenjima. Stoga kontinuirano unapređenje efikasnosti i održivosti fotokatalitičkih sistema predstavlja jedan od ključnih pravaca razvoja savremenih tehnologija za prečišćavanje voda. U ovom radu sintetisani TiO_2 primenjen je kao fotokatalizator za razgradnju metil-ljubičaste boje u vodenom rastvoru. Sistematski je ispitan uticaj početne koncentracije fotokatalizatora na efikasnost procesa razgradnje. Eksperimentalni rezultati pokazali su da je optimalna fotokatalitička efikasnost ostvarena pri koncentraciji TiO_2 od 0,20 g/L i početnoj koncentraciji boje od 10 mg/L. Dobijeni rezultati treba da doprinesu boljem razumevanju fotokatalitičkih procesa i daju značajnu osnovu za razvoj efikasnijih strategija tretmana tekstilnih otpadnih voda.

Ključne reči: *tretman vode, fotodegradacija, TiO_2, organske zagađujuće materije.*

1. INTRODUCTION

The persistence, toxicity, and low biodegradability of many synthetic dyes have made the discharge of dye-containing wastewater from the textile and related industries a significant environmental concern. Conventional wastewater treatment methods often fail to achieve complete removal of these contaminants, highlighting the need for the application of advanced oxidation processes (AOPs) as an effective alternative for wastewater treatment [1].

Because it can mineralize a variety of organic contaminants under benign working circumstances, heterogeneous photocatalysis has become one of these technologies' most promising and ecologically acceptable methods [2]. Due to its exceptional photocatalytic activity, low cost, non-toxicity, and good chemical stability, TiO_2 is the most researched photocatalyst [3].

Dyes represent a significant class of pollutants in industrial wastewater, particularly from the textile, paper, and food industries. Their presence in aquatic environments reduces light penetration, disrupts photosynthetic processes, and adversely affects aquatic organisms [4]. In addition to causing aesthetic pollution, many synthetic dyes are highly persistent, poorly biodegradable, and may exhibit toxic, mutagenic, or carcinogenic properties [5]. Therefore, the efficient removal of dyes from wastewater remains a major challenge in environmental protection and water treatment.

The aim of this study was to evaluate the photocatalytic performance of synthesized TiO_2 in the degradation of methyl violet from aqueous solution, with particular emphasis on the effect of photocatalyst dosage on the degradation efficiency. By identifying the optimal catalyst loading, this research contributes to a better understanding of the operational parameters governing TiO_2-based photocatalytic processes. The obtained results provide useful information for the optimization of photocatalytic systems and support the development of efficient and sustainable technologies for the treatment of dye-contaminated textile wastewater.

2. MATERIALS AND METHODS

Synthesis of biobased material was done according to our previous work [6]. Fabricated photocatalyst was tested in order to determine activity under the imitated sunlight irradiation lamp (Osram Vitalux lamp 300 W, Germany).
Photocatalytic probes were performed in temperately controlled quartz reactor (150 ml). Reaction suspension formed from photocatalyst and dye solution was mixed in dark for the first 30 min, and after under radiation. In certain period, aliquots were sampled and monitored on UV spectrometer (Shimadzu 1800, Japan). The photocatalysis process was monitored for 180 min.

3. RESULTS

Figure 1 shows the degradation curves by varying the initial amount of added photocatalyst.

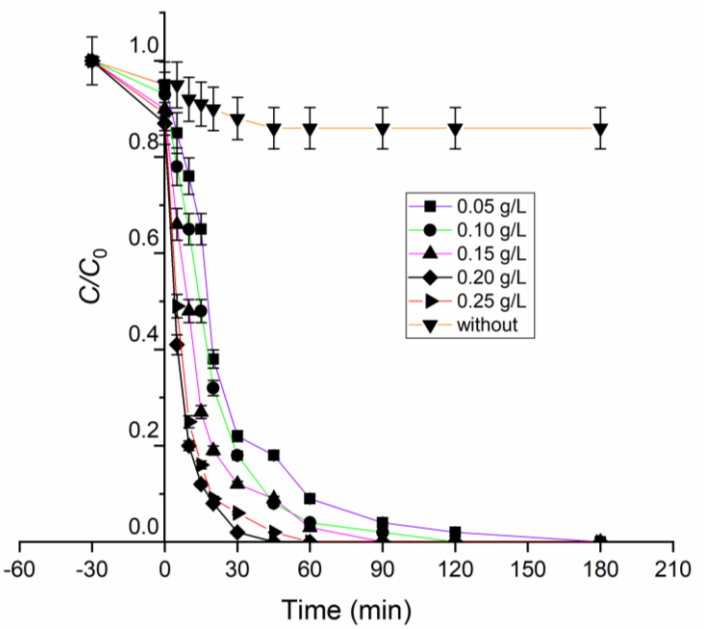

Figure 1: Degradation of MV dye by variyng initial concentration of TiO_2

It was found that at an amount of 0.20 g/l, the degradation percentage was 95%. After 180 min, almost all dye molecules were degradated and observed solution was mostly decolorized. This can be explained by the larger number of active centers for generating electron/hole pairs on the surface of the photocatalyst. Conversely, photolysis does not give prominent results, with degradation rate of only 9%.

4. CONCLUSION

The increasing contamination of aquatic environments by organic pollutants has highlighted the need for the development of efficient and environmentally sustainable advanced oxidation processes (AOPs). Among these, heterogeneous photocatalysis has attracted considerable attention due to its high degradation efficiency, low energy consumption, and potential for complete mineralization of organic contaminants. Continuous improvement of photocatalytic performance and sustainability remains a key research focus in wastewater treatment.

The results of this study demonstrate that synthesized TiO_2 is an effective photocatalyst for the degradation of methyl violet under simulated solar irradiation. Photocatalytic performance was strongly influenced by the catalyst dosage, with the highest degradation efficiency of 95% achieved at a TiO_2 concentration of 0.20 g/L after 180 min of irradiation. The improved performance at the optimal catalyst loading can be attributed to the increased number of active sites available for the generation of electron–hole pairs and the subsequent formation of reactive oxidative species. These findings confirm the potential of TiO_2-based photocatalysis as an efficient and environmentally friendly approach for the treatment of dye-contaminated wastewater. Furthermore, the obtained results contribute to the optimization of photocatalytic operating conditions and support the development of sustainable technologies for industrial wastewater purification.

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MANAGEMENT SYSTEMS AND TOOLS FOR ASSESSING SUSTAINABILITY IN THE TEXTILE INDUSTRY

Professional paper
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ABSTRACT: *The textile industry faces significant environmental and social challenges due to high consumption of natural resources, intensive use of chemicals, waste generation and the need to improve working conditions along the supply chain. In order to respond to these challenges, various sustainability management systems, international standards, certification systems and tools for evaluating the sustainable performance of organizations have been developed. The aim of this paper is to present the basic systems and tools that are applied to assess and improve sustainability in the textile industry, with special reference to ESG platforms, EcoVadis, amfori BSCI, OEKO-TEX®, GOTS, Higg Index® and LCA methodology. The paper analyses their role in monitoring the environmental, social and management aspects of business is along with their importance for increasing transparency, traceability and responsible management of the supply chain. Application of the mentioned systems and tools enables textile organizations to identify risks, measure sustainability performance and define measures for continuous business improvement. Their integration represents an important step towards the transition of the textile industry to a more sustainable and circular model of development.*

Keywords: *sustainability, ESG, EcoVadis, Higg Index, GOTS, OEKO-TEX.*

SISTEMI UPRAVLJANJA I ALATI ZA VREDNOVANJE ODRŽIVOSTI U TEKSTILNOJ INDUSTRIJI

APSTRAKT: *Tekstilna industrija suočava se sa značajnim ekološkim i društvenim izazovima usled velike potrošnje prirodnih resursa, intenzivne upotrebe hemikalija, generisanja otpada i potrebe za unapređenjem uslova rada duž lanca snabdevanja. U cilju odgovora na ove izazove razvijeni su različiti sistemi upravljanja održivošću, međunarodni standardi, sertifikacioni sistemi i alati za vrednovanje održivih performansi organizacija.*

Cilj ovog rada je prikaz osnovnih sistema i alata koji se primenjuju za procenu i unapređenje održivosti u tekstilnoj industriji, sa posebnim osvrtom na ESG platforme, EcoVadis, amfori BSCI, OEKO-TEX®, GOTS, Higg Index® i LCA metodologiju. Analizirana je njihova uloga u praćenju ekoloških, društvenih i upravljačkih aspekata poslovanja, kao i njihov značaj za povećanje transparentnosti, sledljivosti i odgovornog upravljanja lancem snabdevanja. Primena navedenih sistema i alata omogućava tekstilnim organizacijama identifikaciju rizika, merenje performansi održivosti i definisanje mera za kontinuirano unapređenje poslovanja. Njihova integracija predstavlja važan korak ka prelasku tekstilne industrije na održiviji i cirkularni model razvoja.

Ključne reči: *održivost, ESG, EcoVadis, Higg Index, GOTS, OEKO-TEX.*

1. INTRODUCTION

The textile industry represents one of the most important industrial sectors at the global level; however at the same time it is counted among the industries with a considerable impact on the environment and society. High consumption of water and energy, intensive use of chemicals, greenhouse gas emissions and the generation of large amounts of textile waste represent the key challenges this sector is facing [1-2].
In addition to environmental aspects, issues of safety and health of employees, respect for human rights and responsible management of the supply chain are of increasing importance. Contemporary demands of the market, consumers and regulatory bodies brought about the need for a systemic approach to sustainability management in textile organizations [3].
The aim of this paper is to showcase the basic sustainability management systems in the textile industry, as well as the importance of applying international standards, certification systems, ESG (Environmental, Social and Governance) platforms and other tools for evaluating sustainability in improving sustainable business and competitiveness of textile organizations.

2. SUSTAINABILITY IN THE TEXTILE INDUSTRY

The textile industry is considered one of the largest consumers of natural resources and a significant source of environmental pollution. During the textile production process, large amounts of water and energy are consumed, various chemicals are used, and significant amounts of waste and emissions of harmful substances are generated [4].
The processes of dyeing, printing and final processing of textiles, which are associated with intensive consumption of water and chemical agents, represent a special challenge. In addition, the growth in the production and consumption of textile products has led to an increase in the amount of textile waste and a shortening of the product's life cycle, which further burdens the environment [5].

The concept of sustainability in the textile industry is based on establishing a balance between environmental, social and economic aspects of business. Environmental sustainability implies rational use of resources, reduction of energy and water consumption, application of more environmentally friendly chemicals and efficient waste management. Social sustainability includes the protection of health and safety of employees, respect for labor rights and responsible management of the supply chain, while economic sustainability refers to the long-term profitability and competitiveness of the organization [2-3].

3. SUSTAINABILITY MANAGEMENT SYSTEMS, ESG PLATFORMS AND TOOLS FOR SUSTAINABILITY EVALUATION IN THE TEXTILE INDUSTRY

Effective sustainability management in the textile industry requires a systematic approach that includes planning, implementation, monitoring and improvement of the organization's environmental, social and economic performance. To this end, numerous international standards, certification systems and sustainability assessment tools have been developed that enable organizations to identify risks, improve business processes and increase business transparency.

Among the most important standards are sistems for quality management (ISO 9001), environmental protection (ISO 14001), occupational health and safety (ISO 45001) and energy management (ISO 50001). The integrated application of ISO 9001, ISO 14001, ISO 45001 and ISO 50001 standards enables organizations to use resources more efficiently, reduce negative impacts on the environment and improve the working conditions of employees [6-9].

In addition to management system standards, specialized tools and certification systems aimed at assessing sustainability and social responsibility play a significant role in the textile industry. Among these, the following stand out: EcoVadis platform for sustainability assessment, the amfori BSCI (Business Social Compliance Initiative) - a social compliance system in the supply chain, the OEKO-TEX® textile safety standards, the GOTS (Global Organic Textile Standard) for the certification of organic textile products and the Higg index® for evaluating the environmental and social performance of materials, products, production processes and locations [10-14].

The modern concept of sustainability management is increasingly based on ESG principles, which include monitoring the environmental, social and management aspects of business. The application of these principles enables organizations to respond to the demands of customers, investors and regulatory bodies, while increasing their competitiveness and resistance to market changes [3]. Sustainability management systems need to be distinguished from sustainability assessment tools. Management systems represent the organizational framework for planning, implementation, monitoring and continuous improvement of the organization's environmental, social and economic performance. In contrast, sustainability evaluation tools are used to assess the level of development of sustainable practices and the performance of an organization or its suppliers.

EcoVadis is a globally recognized platform for evaluating a company's ESG performance, i.e. environmental, social and management aspects of business, which enable a standardized evaluation of the level of development of the sustainability management system. The assessment is based on the analysis of policies, implemented activities and achieved results of the organization, which includes four key areas: environmental protection, labor and human rights, ethical business and sustainable procurement [10].

The methodology of the EcoVadis system is based on the principle of performance scoring, where companies are evaluated against international standards and best practices in the industry. Based on the obtained results, a ranking is made and a sustainability score is assigned, which enables the comparison of companies within the same or related sectors.

In the textile industry, EcoVadis is most often used as a tool for assessing suppliers in the supply chain, which enables the identification of environmental and social risks, as well as the improvement of business transparency. It is particularly important in the control of working conditions, management of chemicals, reduction of the ecological footprint and compliance with customer requirements.

Application of the EcoVadis methodology contributes to increasing responsibility in the supply chain, strengthening ESG performance and improving the competitiveness of textile organizations on the global market.

Amfori BSCI (Business Social Compliance Initiative) is an international framework for assessing and improving social responsibility in global supply chains, with a special focus on the textile industry, developed by the amfori organization [11]. This system is not used for product certification; instead, it is a framework for evaluating and continuously improving the social performance of suppliers. BSCI is based on a code of conduct that includes basic principles such as the prohibition of child and forced labor, the provision of safe and healthy working conditions, respect for working hours and fair remuneration, as well as the prohibition of discrimination. The implementation of the system is carried out through evaluations and audits of suppliers, as well as defining corrective measures in cases of confirmed non-conformities. In this way, amfori BSCI contributes to increasing transparency and responsibility in the supply chain, as well as improving the social dimension of sustainability in the textile industry.

OEKO-TEX® is an international certification and testing system that is an important tool for evaluating sustainability and safety in the textile industry. It includes various standards that assess the safety of textile products, production conditions and the impact of production processes on the environment. The most famous standard, STANDARD 100 by OEKO-TEX® confirms that textile products have been tested for the presence of harmful substances and are safe for use. In addition, standards such as STeP by OEKO-TEX® (Sustainable Textile & Leather Production) and MADE IN GREEN by OEKO-TEX® evaluate the sustainability of production processes, chemical management, environmental protection, occupational health and safety, social responsibility and product traceability. Due to its comprehensive approach, OEKO-TEX® represents an important tool for assessing and improving sustainability, quality and transparency in the textile supply chain [12].

GOTS (Global Organic Textile Standard) is the leading international standard for the certification of organic textile products and one of the most important tools for evaluating sustainability in the textile industry. It covers the entire production chain from growing organic fibers, processing and dyeing, to production, packaging and labeling of finished products. In addition to certifying that textiles contain organic fibers, GOTS sets strict requirements regarding environmental protection, responsible use of chemicals, waste and water resources management, as well as respect for social criteria, including safe working conditions, prohibition of child and forced labor, and respect for labor rights. Due to its comprehensive approach, GOTS represents a reliable tool for assessing and improving the sustainability of textile products and production processes [13].

The Higg Index® is a set of standardized sustainability assessment tools for the textile, fashion and footwear industries developed by the Sustainable Apparel Coalition (SAC), an organization now known as Cascale. Its primary purpose is to measure and evaluate the environmental and social impacts of materials, products, production processes and production locations along the entire supply chain. The Higg Index includes multiple modules to assess different aspects of sustainability, including environmental impacts, energy and water consumption, greenhouse gas emissions, chemical management and working conditions. The application of the Higg Index allows textile companies to identify key areas for sustainability improvement, compare performance with industry practices, and make data-based decisions to reduce negative environmental and social impacts [15-19].

4. IMPLEMENTATION OF A SUSTAINABILITY MANAGEMENT SYSTEM IN THE TEXTILE ORGANIZATION

The implementation of a sustainability management system in the textile organization begins with the identification of major environmental, social and economic aspects of the business. Water and energy consumption during the textile dyeing and finishing process, the use of chemicals, the generation of wastewater and textile waste, as well as the working conditions of employees and the management of the supply chain [4-5] are identified as the most significant.

In order to improve environmental performance, the organization can apply measures to reduce water and energy consumption, optimize production processes and increase the scope of waste recycling. Special attention is paid to the choice of chemicals with less of a negative impact on the environment and to the control of their use during production [5].

The social component of sustainability includes improving the safety and health of employees, continuous training of staff and ensuring working conditions in accordance with international standards and principles of social responsibility. At the same time, the organization establishes criteria for the selection and evaluation of suppliers, considering their sustainability practices and compliance with market requirements [12-13].

Monitoring and evaluation of sustainability performances is carried out using appropriate indicators, such as specific consumption of water and energy per unit of product, amount

of waste generated, degree of recycling, number of injuries at work and level of compliance of suppliers with the requirements of sustainable business [11].

In addition to monitoring internal performance indicators, modern textile organizations apply international standards, certification systems and sustainability evaluation tools, such as ISO standards, GOTS, OEKO-TEX, Higg Index and BSCI. Their application enables an objective assessment of environmental, social and management aspects of business, increases the transparency of the supply chain and provides a basis for continuous improvement of sustainability. The analysis of the life cycle of the product (LCA - Life Cycle Assessment) is of particular importance, enabling the identification of key impacts during all stages of the creation of a textile product and the selection of more sustainable materials and technologies [20].

Regulation (EU) 2024/1781 on the ecological design of sustainable products (ESPR - Ecodesign for Sustainable Products Regulation) represents the regulatory framework of the European Union which introduces requirements for the sustainable design of products and the assessment of their impacts during the entire life cycle. In the context of the textile industry, the ESPR represents an important regulatory instrument for the improvement and evaluation of sustainability, as it encourages the measurement and improvement of the environmental performance of products through criteria such as efficient use of resources, reduction of emissions, limiting the use of harmful substances, increasing the durability of products, the possibility of repair, reuse and recycling [21].

The regulation promotes the application of sustainability methods and indicators, especially the product life cycle assessment (LCA) approach, and requires greater transparency along the supply chain. Of particular importance is the introduction of the digital product passport (DPP - Digital Product Passport), which enables the collection and exchange of data on the composition of the product, the origin of materials, environmental characteristics and the possibilities of sustainable management of the product after its use. Within the textile industry, ESPR complements existing sustainability assessment tools such as the Higg Index, GOTS, OEKO-TEX, BSCI and LCA, providing a regulatory basis for more objective measurement, comparison and improvement of the sustainability of textile products. The aim of the regulation is to move from the model of linear production and consumption of textiles to a circular model, while increasing producer responsibility, transparency and sustainability of the entire value chain. In practice, ESPR complements existing sustainability rating systems as it directs manufacturers to look at sustainability not only through product certification, but across the entire life cycle, product design and resource management. The ESPR also introduces requirements that encourage waste reduction, including limiting the destruction of unsold products and improving reuse and recycling systems. The implementation of these requirements is a challenge for the textile industry due to the need to establish effective systems for data collection, product traceability, reuse and recycling of textile products.

5. CONCLUSION

The textile industry faces numerous challenges in the field of environmental protection, rational use of resources and social responsibility, which makes sustainability one of the key factors of its future development. The increasingly pronounced demands of the market, consumers and regulatory bodies require textile organizations to establish a systemic approach to sustainability management and continuous improvement of business processes [1], [3].

The implementation of a sustainability management system enables organizations to manage energy and water consumption more efficiently, reduce negative environmental impacts, improve employee working conditions and manage the supply chain more responsibly. The integration of international standards, certification systems and ESG tools contributes to increased business transparency, better risk management and strengthening the competitive position of organizations on the global market.

ESG sustainability assessment platforms are a modern digital tool that enables the collection, analysis and monitoring of data on the environmental, social and management performance of textile organizations. Their application enables more objective evaluation of sustainability through defined indicators, comparison of results between organizations and identification of areas for improvement. The special importance of ESG platforms is reflected in increasing the transparency of the supply chain, monitoring supplier compliance and supporting decision-making based on reliable data.

In combination with international standards and sustainability assessment tools, such as LCA, Higg Index, GOTS, OEKO-TEX, BSCI and the requirements of the European regulation ESPR, ESG platforms represent an important basis for systematic sustainability management in the textile industry. They enable the transition from individual initiatives to an integrated management model that encompasses the entire product life cycle and the entire value chain.

It can be concluded that sustainability is no longer just a strategic commitment of individual organizations, but a necessary condition for business success in the long run and for the development of the textile industry. Modern systems and tools for sustainability evaluation, including ESG platforms, LCA methodology, certification systems and regulatory frameworks, represent an important element of the transformation of the textile industry towards a more transparent, responsible and circular business model.

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SESSION V

TEXTILE HERITAGE

9. Međunarodna naučna konferencija
„**Savremeni trendovi i inovacije u tekstilnoj industriji**“
17-18. septembar 2026. Beograd, Srbija

ANALYSIS OF BORDER PATTERNS WITH PMM2 SYMMETRY IN MACEDONIAN FOLK COSTUMES

Professional paper
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ABSTRACT: *Border patterns represent one of the most prominent decorative elements in Macedonian folk costumes, combining aesthetic, structural and cultural functions. Among the different classes of patterns developed along a single axis, those exhibiting bilateral symmetry, are of special interest due to their frequent occurrence and balanced visual composition. This study focuses on the analysis of border patterns with bilateral symmetry in Macedonian traditional textiles, with an emphasis on the pmm2 symmetry class. Photographic documentation of traditional costumes from various ethnographic regions was collected and transformed into simplified linear representations for symmetry classification. The patterns were analyzed according to established symmetry principles, identifying the presence of translational repetition combined with vertical and horizontal mirror reflections characteristic of the pmm2 group. Among the analyzed examples, border patterns exhibiting pmm2 symmetry appeared frequently, especially in decorative elements positioned along sleeves, necklines and hems of traditional garments. Their symmetrical structure contributes not only to visual harmony but also to functional stability of the textile elements. The study highlights the importance of bilateral symmetry in preserving cultural identity and offers a basis for contemporary textile design inspired by traditional Macedonian ornaments.*

Keywords: *border patterns, pmm2 symmetry, bilateral symmetry, Macedonian folk costumes, textile ornaments.*

ANALIZA BORDURNIH ORNAMENATA SA PMM2 SIMETRIJOM U MAKEDONSKIM NARODNIM NOŠNJAMA

APSTRAKT: *Bordurni ornamenti predstavljaju jedan od najistaknutijih dekorativnih elemenata u makedonskim narodnim nošnjama, kombinujući estetsku, strukturnu i kulturnu funkciju. Među različitim klasama ornamenata razvijenih duž jedne ose, posebnu pažnju privlače oni koji pokazuju bilateralnu simetriju, zbog svoje česte zastupljenosti i*

uravnotežene vizuelne kompozicije.Ova studija fokusira se na analizu bordurni ornamenata sa bilateralnom simetrijom u makedonskom tradicionalnom tekstilu, sa posebnim osvrtom na pmm2 klasu simetrije. Fotografska dokumentacija tradicionalnih nošnji iz različitih etnografskih regiona prikupljena je i transformisana u pojednostavljene linearne prikaze radi klasifikacije simetrije. Ornamenti su analizirani prema utvrđenim principima simetrije, pri čemu je identifikovano prisustvo translacionog ponavljanja u kombinaciji sa vertikalnim i horizontalnim refleksijama ogledala, karakterističnim za pmm2 grupu.Među analiziranim primerima, bordurni ornamenti sa pmm2 simetrijom javljali su se često, naročito u dekorativnim elementima postavljenim duž rukava, izreza i rubova tradicionalnih odevnih predmeta. Njihova simetrična struktura doprinosi ne samo vizuelnoj harmoniji, već i funkcionalnoj stabilnosti tekstilnih elemenata.Studija ukazuje na značaj bilateralne simetrije u očuvanju kulturnog identiteta i pruža osnovu za savremeni tekstilni dizajn inspirisan tradicionalnim makedonskim ornamentima.

Ključne reči: *bilateralna simetrija, granični ornamenti, makedonske narodne nošnje, pmm2 grupa, tradicionalni tekstil*

1. INTRODUCTION

Traditional textile ornaments represent an important segment of the cultural and visual identity of many nations. Through the arrangement of motifs, colours and compositional structures, textile patterns preserve information about aesthetic values, regional traditions and symbolic meanings developed over centuries [1]. In Macedonian folk costumes, decorative textile elements occupy a significant place, combining artistic expression with functional and structural roles. Embroidered and woven ornaments are positioned on characteristic parts of garments such as sleeves, necklines, hems, aprons and belts, where they contribute to the visual balance and recognisability of the costume [2].

Among the different ornamental compositions found in traditional textiles, border patterns represent one of the most frequently occurring decorative forms. Border patterns are one-dimensional compositions created through the repetition of motifs along a single axis, usually between two imaginary parallel lines. Depending on the applied symmetry operations, these patterns may include translation, mirror reflection and rotational symmetry, resulting in seven primary classes of border symmetry groups [3].

Particularly significant among these classes is the pmm2 symmetry group, characterised by translational repetition combined with both vertical and horizontal mirror reflections. This type of bilateral symmetry creates visually balanced and rhythmically organised compositions, which are especially suitable for decorative applications on garment edges and structural textile elements. In Macedonian traditional costumes, pmm2 border patterns frequently appear in embroidery and woven decorations, contributing not only to the aesthetic harmony of the costume, but also to the reinforcement and visual framing of specific garment parts [4]. Symmetry analysis in traditional textiles represents an important methodological approach for understanding the structural organisation and visual

composition of ornamental patterns. Previous studies have demonstrated that geometric classification of textile ornaments can reveal relationships between decorative forms, cultural identity and design principles applied in traditional fabrics and embroideries [7,8] . In addition to their ethnographic significance, traditional textile patterns also serve as a valuable source of inspiration for contemporary textile and fashion design, contributing to the development of new decorative concepts based on historical motifs and compositional systems [5,6].

Therefore, the aim of this study is to analyse border patterns with pmm2 symmetry in Macedonian traditional textiles and folk costumes, with emphasis on their structural characteristics, frequency of occurrence and decorative role within the textile heritage of North Macedonia.

2. METHODOLOGY

The research was conducted through visual documentation and symmetry analysis of border ornaments found in Macedonian traditional textiles and folk costumes. Photographic material was collected from reproductions of traditional costumes used by national folklore ensembles, including Ensemble “Macedonia”, KAS “Ilinden” – Bitola, KAS “Ilinden” – Struga and KAS “Drimkol” – Vevčani, while an additional part of the material was documented at the Ethnological Museum in Skopje. The analysed ornaments originated from several ethnographic regions of North Macedonia, providing a representative overview of traditional decorative practices.

The selected ornamental samples consisted primarily of embroidered and woven border patterns positioned on characteristic garment elements such as sleeves, necklines, hems, aprons and decorative textile bands. From the collected photographic material, border ornaments exhibiting bilateral symmetry were identified and selected for further analysis.

In order to facilitate the symmetry classification process, the original ornamental compositions were transformed into simplified linear black-and-white representations, allowing clearer identification of symmetry operations and repetitive structural elements. The classification procedure was conducted according to the geometric symmetry principles proposed by Washburn and Crowe [9], with emphasis on one-dimensional border symmetry groups.

The analysis focused specifically on the pmm2 border symmetry class, characterised by translational repetition combined with vertical and horizontal mirror reflections. Each selected pattern was examined in terms of the presence and arrangement of symmetry operations, motif repetition, compositional balance and structural organisation. In addition to the symmetry classification, observations regarding the decorative placement and functional role of the analysed ornaments within the garment structure were also considered.

The obtained results were comparatively evaluated in order to determine the frequency and visual characteristics of pmm2 border patterns in Macedonian traditional textiles, as well as their contribution to the aesthetic and cultural identity of folk costume ornamentation.

3. RESULTS AND DISCUSSION

3.1. Occurrence of pmm2 border patterns in Macedonian folk costumes

The conducted symmetry analysis included 22 border ornaments exhibiting pmm2 symmetry from Macedonian traditional textiles. The analysed patterns were characterised by translational repetition combined with vertical and horizontal mirror reflections, which are characteristic features of the pmm2 symmetry class. The results confirm the significant presence of bilateral symmetry in the visual organisation of traditional Macedonian ornamentation.

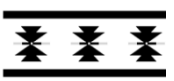
No.	Class (Region)	Sketch	Sample
a.	p’mm2 (2)		
b.	p’mm2 (2)		
c.	pmm2 (2)		

Figure 1. Examples of pmm2 border patterns identified in Macedonian traditional textiles

The analysed pmm2 border patterns were identified in several ethnographic regions of North Macedonia and appeared on different textile and garment elements, particularly on shirt sleeves, necklines, hems, aprons and decorative woven bands. Their frequent application on garment edges indicates both decorative and structural importance within traditional costume composition. In embroidered textiles, pmm2 patterns were often used to visually frame specific parts of the garment, creating balanced ornamental transitions between structural textile elements.

3.2. Structural characteristics of pmm2 symmetry

The pmm2 symmetry group is characterised by translational repetition combined with vertical and horizontal mirror reflections, resulting in highly ordered and rhythmically organised border compositions.

No.	Class (Region)	Sketch	Sample
a.	pmm2 (1)		
b.	pmm2 (5)		
c.	pmm2 (1)		

Figure 2. Linear reconstructions of a pmm2 border ornaments showing translational repetition and bilateral mirror symmetry

The analysed patterns demonstrated a clear repetition of ornamental motifs along a single axis, while the simultaneous presence of mirror reflections contributed to the formation of balanced bilateral structures.

In most examined examples, the motifs were geometrically stylised and arranged in repetitive sequences that generated visual continuity and compositional stability. The symmetry operations created a pronounced rhythmic effect, emphasising the linear character of the border ornament. In addition, the use of mirrored motifs contributed to the perception of harmony and regularity, which represents one of the defining visual characteristics of pmm2 border patterns. The characteristic symmetry operations of the pmm2 border group, including translational repetition and bilateral mirror reflections, are schematically presented in Figure 3.

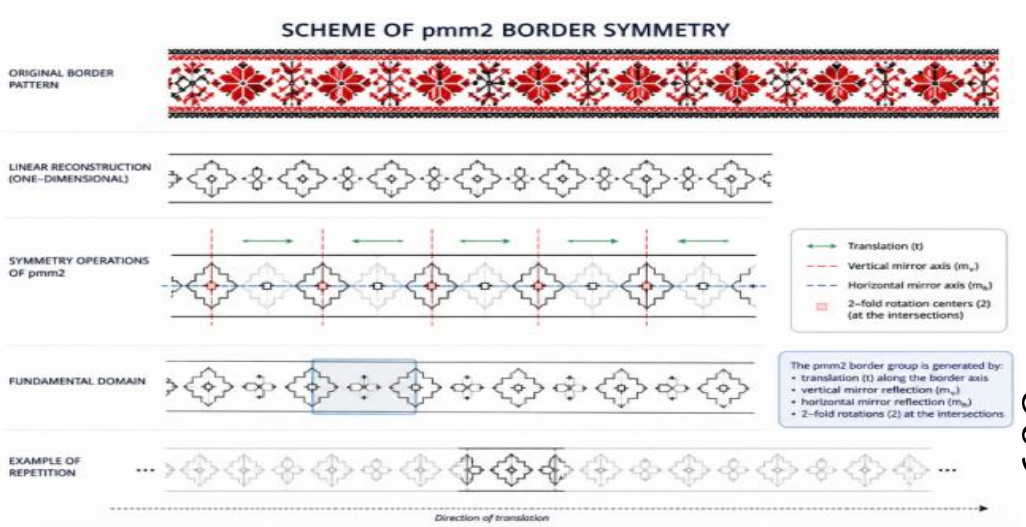


Figure 3. Symmetry operations characteristic for the pmm2 border group

Certain variations in motif size, internal decorative details and colour arrangement were also observed among the analysed samples. However, despite these minor visual modifications, the fundamental geometric structure of translational repetition combined with double mirror reflection remained preserved.

3.3. Decorative and functional role of pmm2 border patterns

Besides their decorative value, pmm2 border patterns also possess an important functional role within traditional textile constructions. Their placement on garment edges contributes to the visual definition and framing of structural clothing elements, while embroidered borders additionally reinforce textile areas exposed to frequent mechanical stress, such as sleeve endings and neckline edges.

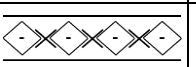
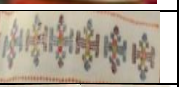
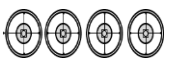
No.	Class (Region)	Sketch	Sample
a.	p’mm2 (5)		
b.	p’mm2 (5)		
c.	pmm2 (4)		

Figure 4. Application of pmm2 border ornaments on characteristic elements of Macedonian folk costumes

The balanced composition achieved through bilateral symmetry enhances the visual harmony of the costume and contributes to the recognisability of traditional Macedonian textile ornamentation. The repetitive and geometrically organised structure of pmm2 borders also reflects the technical skills and aesthetic principles developed within traditional embroidery and weaving practices.

Furthermore, the analysed ornaments demonstrate the strong relationship between geometric organisation and cultural expression in traditional textiles. Through the preservation and transmission of ornamental structures across generations, pmm2 border patterns became an integral part of the visual identity of Macedonian folk costumes.

3.4. Relevance of pmm2 symmetry for contemporary textile design

Traditional border ornaments continue to represent a valuable source of inspiration for contemporary textile and fashion design. The geometric clarity, rhythmic repetition and balanced structure characteristic of pmm2 symmetry provide possibilities for reinterpretation within modern decorative compositions, woven structures, printed textiles and fashion applications.

The study of traditional symmetry systems contributes not only to the preservation of cultural heritage, but also to the development of innovative design solutions derived from

historical ornamental principles. In this context, pmm2 border patterns represent an important connection between traditional textile heritage and contemporary design practices.

4. CONCLUSION

The conducted study confirmed that border ornaments with pmm2 symmetry represent one of the most dominant and visually characteristic decorative structures in Macedonian traditional textiles and folk costumes. The analysed patterns demonstrated a consistent application of translational repetition combined with vertical and horizontal mirror reflections, resulting in balanced and rhythmically organised ornamental compositions.
The frequent occurrence of pmm2 border patterns on garment edges, sleeves, necklines and woven decorative bands indicates both their aesthetic and structural significance within traditional textile constructions. Besides contributing to visual harmony and compositional balance, these ornaments also reflect the cultural identity and traditional craftsmanship preserved through generations.
The obtained results demonstrate that symmetry analysis represents an effective methodological approach for the classification and interpretation of traditional textile ornaments. Furthermore, the geometric organisation and decorative principles of pmm2 border patterns may serve as valuable inspiration for contemporary textile and fashion design based on traditional cultural heritage.

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FORMAL AND CONCEPTUAL CONTEXTS OF TRADITIONAL CROSS-STITCH TECHNIQUES IN CONTEMPORARY ART AND INSTALLATION EXAMPLES

Scientific Paper
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ABSTRACT: *Traditional cross-stitch, one of the heritage handicrafts, dates back to ancient times. The earliest examples of this embroidery are found in Asia, from where it is known to have spread to Europe. The methods of use, application areas, and meanings of cross-stitch vary across every civilization. Having historically found wide application in garments, home textiles, and accessories, cross-stitch embroidery has begun to gain new meaning within contemporary art. Cross-stitch is an embroidery technique consisting of superimposed and juxtaposed needlework patterns formed by shapes that intersect each other in an X form. Depending on the characteristics of the fabric applied, it is a type of embroidery performed either by counting the threads of the fabric itself or, on fabrics where threads cannot be counted, by counting the strands of a canvas mesh used as an auxiliary tool. The sustainability of traditional arts and their transmission to new generations represent a significant potential for today's contemporary art and installation. Within the scope of this research, the adaptation of cross-stitch as a cultural heritage element onto textile surfaces and works intersecting at the innovation of "from craft to art" have been examined. Document analysis was utilized as the data collection technique for the research methodology. Reinterpreting traditional cross-stitch motifs, harmonizing handicrafts with industrial designs, and establishing advanced communication between technology and cultural heritage are necessities of our age. New formal and conceptual interpretations of cross-stitch will provide futuristic perspectives to contemporary art.*

Keywords: *Cross-stitch, Textiles, Installation, Cultural heritage, Conceptual art.*

FORMALNI I KONCEPTUALNI KONTEKST TRADICIONALNIH TEHNIKA KRSTASTOG VEZA U SAVREMENOJ UMETNOSTI I PRIMERIMA INSTALACIJA

APSTRAKT: *Tradicionalni krstasti vez jedan od tradicionalnih rukotvorina, datira iz antičkih vremena. Najraniji primeri ovog veza nalaze se u Aziji, odakle se, kako se zna, proširio u Evropu. Metode upotrebe, oblasti primene i značenja krstastog veza razlikuju se u svakoj civilizaciji. Nakon što je istorijski pronašao široku primenu u odeći, kućnom tekstilu i dodacima, krstasti vez je počeo da dobija novo značenje u savremenoj umetnosti. Krstasti vez je tehnika veza koja se sastoji od preklopljenih i suprotstavljenih uzoraka veza formiranih oblicima koji se međusobno seku u obliku slova X. U zavisnosti od karakteristika primenjene tkanine, to je vrsta veza koja se izvodi ili brojanjem niti same tkanine ili, na tkaninama gde se niti ne mogu brojati, brojanjem niti platnene mreže koja se koristi kao pomoćni alat. Održivost tradicionalnih umetnosti i njihov prenos na nove generacije predstavljaju značajan potencijal za današnju savremenu umetnost i instalacije. U okviru ovog istraživanja ispitana je adaptacija krstastog veza kao elementa kulturnog nasleđa na tekstilne površine i radove koji se presecaju na inovaciji „od zanata do umetnosti“. Analiza dokumenata je korišćena kao tehnika prikupljanja podataka za metodologiju istraživanja. Reinterpretacija tradicionalnih motiva krstastog veza, harmonizacija rukotvorina sa industrijskim dizajnom i uspostavljanje napredne komunikacije između tehnologije i kulturnog nasleđa su neophodnosti našeg doba. Nova formalna i konceptualna tumačenja krstastog veza pružiće futurističke perspektive savremenoj umetnosti.*

Ključne reči: *krstasti vez, tekstil, instalacija, kulturno nasleđe, konceptualna umetnost.*

1. INTRODUCTION

The earliest examples of cross-stitch embroidery are found in Asia, from where the technique is understood to have spread to Europe. The functions, application areas and motif meanings of cross-stitch differ across civilizations. Historically used in clothing, home textiles and accessories, cross-stitch has recently begun to regain its former cultural and aesthetic importance [1].

Cross-stitch is an embroidery technique made of superimposed and side-by-side needlework forms that intersect each other diagonally (Figure 1). In Europe, the technique is known by the term “cross stitch”, which corresponds to the Turkish meaning of “çapraz dikiş” [2].

Although it is not possible to state with certainty when and where the art of embroidery first emerged, archaeologists have identified various findings related to embroidery in Hittite, Egyptian, Mesopotamian, Assyrian, Iranian, Greek and Anatolian civilizations. Many artefacts from Central Asia also indicate the long historical presence of embroidery practices [2].

Depending on the characteristics of the fabric, cross-stitch may be applied by counting the threads of the fabric itself or, when the fabric threads cannot be counted, by using a canvas mesh as an auxiliary counted surface. In the cross-stitch process, the needle is brought up from below and inserted diagonally upward to create slanted thread movements (Figure 2).

The process continues until the end of the row, and the return pass is completed by crossing over the previous stitches [2].

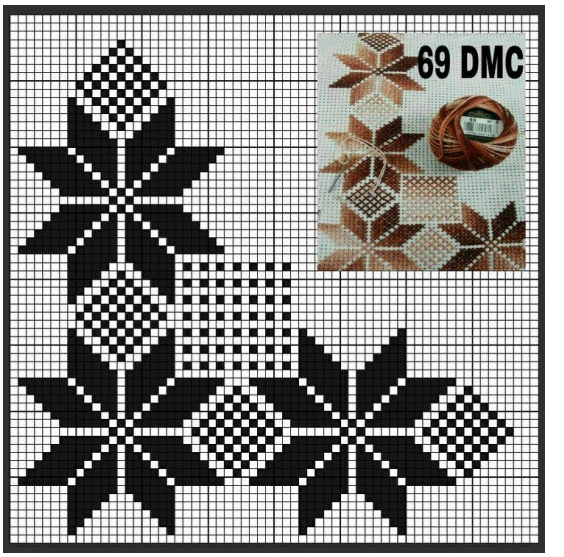

Figure 1: Cross-stitch example [3]

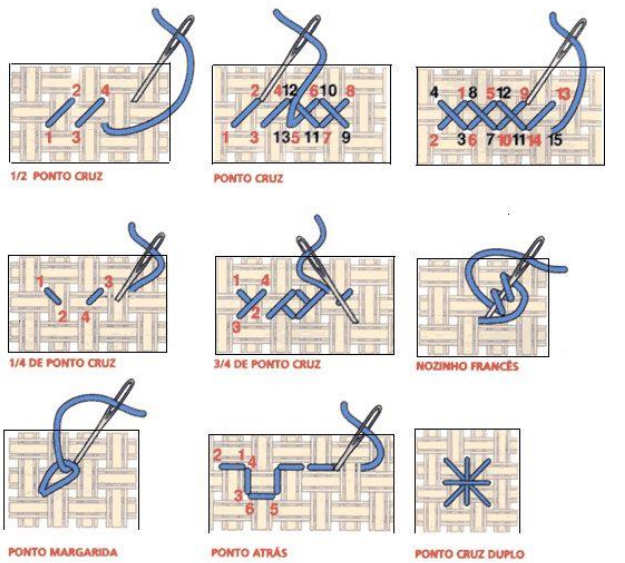

Figure 2: Cross-stitch embroidery technique [4]

This paper evaluates contemporary interpretations of traditional cross-stitch embroidery as practices that can provide new, future-oriented perspectives for textile, fashion and installation art. Reinterpreting traditional motifs, aligning handicrafts with industrial design and contemporary art, and establishing a more developed dialogue between technology and cultural heritage are central concerns of the present age.

2. TRADITIONAL CROSS-STITCH ART, CONTEMPORARY DESIGNS AND INSTALLATION

Fashion's sustained interest in creativity and production encourages designers to renew and develop their practices continuously. In the designs of Zeynep Tosun, where cultural, local, ethnic, eclectic and traditional references meet, it is possible to observe both the innovative character of fashion and the modern reflection of tradition [5].

By carrying colors and traditional motifs into her collections in a contemporary manner, Zeynep Tosun has contributed to the transmission and visibility of cultural values. She has transferred motifs that convey the feelings and thoughts of Anatolian women into her collections through cross-stitch embroidery techniques [6].

Figure 3: Zeynep Tosun 2016-2017 autumn/winter collection with cross-stitch motifs [7]

In addition to meeting functional needs, a textile product should also possess design value. This value can be assessed through the aesthetic response created by the product. A product designed for aesthetic quality should be original, visually distinctive among comparable products, innovative and contemporary. These criteria strengthen design value and support the product's commercial relevance and preference [8].

Ana Martin, a Portuguese textile artist known as Aheneah, works at the intersection of traditional textiles and contemporary art. She produces new textile structures by using fibers, bioplastics and unconventional materials, and has created public art installations across Europe as well as exhibitions in Europe and the United States.

The installation works of Lisbon-based artist and designer Ana Martin become visually clear when the viewer steps back from the surface. Using only wool and nails, the artist creates large-scale cross-stitch compositions on walls and buildings. When observed closely, the work appears as a carefully arranged accumulation of colors and fibers on a grid; from a distance, it becomes a legible figurative image. The pixelated appearance of these works is not accidental, since Martin aims to make cross-stitch more appealing to the digital generation.

One of Martin's works, titled Freedom, includes technical references to cross-stitch and was exhibited in an urban art festival context, expanding the technique from domestic and textile surfaces into public space.

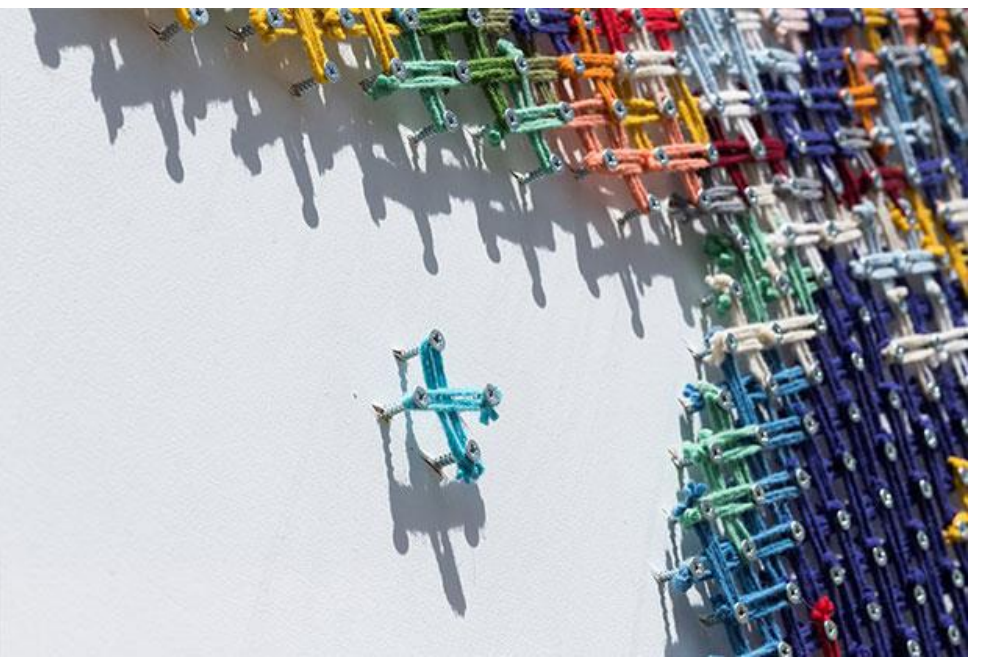

Figure 4: Close-up of an Ana Martin work inspired by cross-stitch technique [9]

Figure 5: Passage, exhibited in Vila Franca de Xira, Ana Martin, 2018 [9]

Figure 6: Freedom, exhibited at an urban art festival, Ana Martin, 2021 [10]

In the work of ceramic artist Caroline Harrius, embroidery finds a different material ground. Harrius frequently addresses gender hierarchies within craft history and their effects on contemporary artistic practice. In one of her ceramic vase works, she uses the cross-stitch technique on a ceramic surface. Before firing, the surface is pierced according

to the needle movements of embroidery; after firing, colored threads are used to complete the motif. Through such combinations of ceramic and embroidery, Harrius seeks to highlight cultural heritage and make it visible to new audiences [11].

Figure 7: Caroline Harrius, 2022, embroidery on ceramic, thread/cross-stitch embroidery [11]

Screenwriter and artist Raquel Rodrigo has brought her cross-stitch installation works, produced with thick, rope-like colored yarns, into the streets of Madrid. The installations are created by applying cross-stitch techniques to wire meshes with rope-like threads. These decorative pieces operate as playful, pixelated textures that can appear very different when viewed from close range and from a distance [12,13].

Figure 8: Raquel Rodrigo's ArquiCostura technique combining architecture and embroidery [13]

Figure 9: Cross-stitch technique applied by Raquel Rodrigo using rope-like colored yarns [13]

In contemporary art, it is possible to speak of an approach in which disciplinary boundaries are increasingly fluid and different materials and concepts are used together. In any new discourse developed around a cultural or traditional term, the decisive element is the new narrative created by the artist. The combined use of concepts from different disciplines produces a new artistic practice and an alternative language within art [14].

3. CONCLUSION

This study demonstrates that traditional cross-stitch is not merely a decorative technique belonging to the past, but a powerful expressive language within contemporary art and design disciplines. In its historical trajectory from Asia to Europe, cross-stitch was once largely associated with clothing and home textiles; today, however, it operates as an interdisciplinary bridge. The basic X form of cross-stitch establishes an aesthetic parallel with the pixel logic of the digital age. As seen in the example of Ana Martin (Aheneah), the transfer of small-scale traditional embroidery into large urban installations redefines cross-stitch within the context of public art. Spanish artist Raquel Rodrigo similarly moves colorful, large-scale cross-stitch installations into the streets of Madrid through wire mesh and thick, rope-like yarns [13].

The synthesis of traditional cross-stitch techniques and motifs with futuristic forms in Zeynep Tosun’s fashion collections creates a modern interface for transmitting cultural heritage to younger generations. The integration of handicrafts into industrial design is important for a sustainable cultural cycle. The work of artists such as Caroline Harrius, who combines embroidery with hard surfaces such as ceramics, blurs the sharp boundaries between craft and art. This transformation shows that cross-stitch, traditionally coded as domestic women’s labor, can become a conceptual instrument that questions gender roles

and craft hierarchies within contemporary art. Through its mathematical structure and universal visual language, cross-stitch will continue to occupy a productive position at the intersection of technology, art and craft. Such innovative reinterpretations of tradition offer future-oriented perspectives for art while also supporting the preservation of cultural memory.

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9. Međunarodna naučna konferencija
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KNOTTING TECHNIQUE AS A SUSTAINABLE SOLUTION FOR TEXTILE WASTE MANAGEMENT AND HUMANITARIAN SUPPORT

Professional paper
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ABSTRACT: *The increasing generation of textile waste and the growing environmental and humanitarian challenges of modern society have highlighted the need for sustainable and resource efficient solutions. Traditional textile techniques offer valuable opportunities to address these issues through the principles of reuse, repair, and responsible resource management. Among these techniques, knotting stands out as a simple, accessible, and sustainable method that requires minimal tools and allows the effective utilization of textile waste materials. This paper examines the potential of the knotting technique as a sustainable approach within the textile sector and its application in humanitarian contexts. The technique enables the transformation of discarded textiles, fabric scraps, and used clothing into functional and durable products such as rugs, bags, baskets, mats, and decorative items. In addition to reducing textile waste, knotting promotes material reuse, extends product lifespan, and supports circular economy principles. By encouraging creativity, waste reduction, and the production of durable and repairable products, it contributes to environmental protection while simultaneously offering social and humanitarian benefits.*

Keywords: *Knotting technique, textile waste, sustainability, humanitarian support, traditional textile techniques.*

TEHNIKA ČVOROVANJA KAO ODRŽIVO REŠENJE ZA UPRAVLJANJE TEKSTILNIM OTPADOM I HUMANITARNU PODRŠKU

APSTRAKT: *Rastuća proizvodnja tekstilnog otpada i sve veći ekološki i humanitarni izazovi savremenog društva istakli su potrebu za održivim i resursno efikasnim rešenjima.*

Tradicionalne tekstilne tehnike nude dragocene mogućnosti za rešavanje ovih problema kroz principe ponovne upotrebe, popravke i odgovornog upravljanja resursima. Među ovim tehnikama, tehnika čvorovanja izdvaja se kao jednostavna, pristupačna i održiva metoda koja zahteva minimalan broj alata i omogućava efikasno korišćenje tekstilnog otpadnog materijala. Ovaj rad ispituje potencijal tehnike čvorovanja kao održivog pristupa u tekstilnom sektoru i njenu primenu u humanitarnim kontekstima. Tehnika omogućava pretvaranje odbačenog tekstila, ostataka tkanina i stare odeće u funkcionalne i dugotrajne proizvode, kao što su prostirke, torbe, korpe, podmetači i dekorativni predmeti. Pored smanjenja količine tekstilnog otpada, čvorovanje podstiče ponovnu upotrebu materijala, produžava životni vek proizvoda i podržava principe cirkularne ekonomije. Podsticanjem kreativnosti, smanjenja otpada i izrade trajnih i popravljivih proizvoda, ova tehnika doprinosi zaštiti životne sredine, a istovremeno pruža značajne društvene i humanitarne koristi.

Ključne reči: *Tehnika čvorovanja, tekstilni otpad, održivost, humanitarna podrška, tradicionalne tekstilne tehnike.*

1. INTRODUCTION

The world today faces two major problems, one is the increasing number of humanitarian crises, and the other is the increasing amount of textile waste. On the one hand, the world is facing an increasing number of humanitarian crises caused by wars, natural disasters, poverty, unemployment, climate change, pollution and epidemics [1]. These crises, are events or a series of events that pose significant threats to the health, safety, or well-being of a community or large group of people, affecting millions of people worldwide [2]. As a result, millions of people are left without essential textile products such as clothes, blankets, bedding, and other textile items necessary for their safety and dignified life.
On the other hand, the fashion industry, especially the concept of fast fashion [3] creates huge amounts of textile waste that end up in landfills even though many of these products can still be reused or recycled. Excessive production and consumption not only pollute the environment, but also represent an irrational use of resources [4,5,6].
Although these problems seem unrelated, they are actually closely related and can have a common approach in solving them. The contradiction that arises indicates the need for more efficient management of textile resources and their targeting to those who need them most.

2. TRADITIONAL TEXTILE TECHNIQUES AS A PATH TO A SUSTAINABLE FUTURE: KNOTTING TECHNIQUE

In conditions of increasing environmental challenges and an increasing amount of textile waste, modern society is looking for new solutions for sustainable production and

consumption. Interestingly, some of these solutions are not new, but originate from traditional textile techniques that have been used in everyday life for centuries [7,8,9]. Today, they represent a significant source of inspiration for the development of a sustainable textile industry. Traditional methods of textile production are characterized by low energy consumption, minimal waste generation and high durability of products [10]. Among them are hand weaving, patchwork, rag braiding and knotting, knitting and repairing stitching [10,11]. These techniques allow for maximum use of materials and greatly increase the longevity of textile products.

Unlike the concept of fast fashion, which encourages mass production and short-term use of clothing, traditional techniques are based on the principles of reuse, repair and responsible use of resources. That is why they can contribute to reducing textile waste and preserving the environment [10].

In addition to the environmental benefits, these techniques also have a significant humanitarian dimension [10]. By applying them, useful textile products can be created from reused materials, which can then be used in humanitarian crises, caused by natural disasters, armed conflicts or mass migrations, often create a need for quick, accessible and sustainable solutions to provide basic living conditions. In such situations, the knotting technique is a practical and efficient way to utilize available resources and reduce waste.

This technique is distinguished by the fact that it requires a minimum number of tools. In most cases, only hands and textile material are sufficient, which makes it accessible to people of different ages and skill levels. In addition, knotting is easy to learn, as it is based on the repetition of simple knots that can be quickly mastered.

One of the greatest advantages of this technique is the possibility of reusing textile waste. Fabric scraps, old clothes or unused textile products can be given a new life by making functional objects such as bags, mats, baskets, decorative elements and other useful products for everyday use.

Products made with the knotting technique are durable and long-lasting. Thanks to the strength of the knots, they can withstand daily use without easy damage. If damage does occur, such products are easily repaired by retying or replacing a certain part, which further extends their lifespan.

With its simplicity, economy and environmental value, the knotting technique is an excellent example of a sustainable approach in the textile industry. It not only contributes to the reduction of textile waste, but also encourages creativity, the reuse of materials and the creation of functional, durable and repairable products [11].

3. APPLICATION OF THE KNOTTING TECHNIQUE

The knotting technique has a wide range of applications in the production of both functional and decorative textile products. Due to its simplicity, flexibility, and ability to utilize recycled materials, it can be adapted to different purposes and user needs.

The knotting technique is widely used in the creation of rugs and mats. Durable floor coverings of various forms, sizes, and patterns can be constructed by attaching fabric strips

using a series of knots. These products are particularly valued for their strength, comfort, and ability to incorporate textile waste into a new functional form.
The technique is also commonly used to create bags, baskets, and storage containers. These devices offer practical ways for organizing home things while also encouraging the reuse of unwanted fabrics. Depending on the material and knot structure, products can range from lightweight decorative pieces to strong containers appropriate for daily usage.
Knotting can also be used to create home decor items such as wall hangings, cushions, table mats, tablecloth (Fig. 1 a) plant holders, and decorative ornaments. The technique's adaptability enables designers and craftspeople to experiment with various colors, textures, and patterns, resulting in one of kind handmade goods.
The knotting technique is equally appropriate for the fabrication of humanitarian and community-support objects. Using recycled fabrics, communities can make rugs (Fig 1 b), blankets, sitting mats, bags, and other useful items that can be provided to disadvantaged groups or utilized in emergencies. Because the technique requires minimal tools and training, it can be implemented in workshops (Fig. 1 c), educational programs, and social initiatives aimed at promoting sustainability and self-sufficiency.
Furthermore, knotting can be used in modern textile design and ecological fashion. Belts, jewelry, hats (Fig. 1 d), keychains, and decorative embellishments for garments can be made from textile leftovers, helping to reduce waste and promote circular design practices.
The knotting process, with its various uses, demonstrates how ancient textile expertise can be converted into creative and sustainable goods. Its capacity to combine functionality, durability, inventiveness, and environmental responsibility makes it an invaluable tool for both personal use and larger social and environmental efforts.
The images shown in Figure 1 are products created by students within a workshop organized by Faculty of Technology, Goce Delcev University, Stip, on the topic Textiles in Humanitarian Crises and Reviving Traditional Textile Techniques.

Tablecloth (a) Rug (b)

Workshop (c) Hat (d)

Figure 1: Products created by students at a workshop organized at the Faculty of Technology, Goce Delcev University, Stip

3.1. Making a rug from rags using the knotting technique

1. **Materials and tools.** To knit a rug, you need a needle and strips of fabric. Make fabric strips by cutting and tearing the fabric or old cloths along the warp or weft yarns. Cut a hole at each end of your fabric strips, as indicated in figure 2.

Figure 2: Preparing fabric strips

2. **Connect the strips**. Insert one strip with the end with the hole through the hole of the other. Insert the other end of the first strip into its hole. Hold ends of the both strips witch are without holes and pull them apart, figure 3.

Figure 3: Connecting the strips

3. **Make the first knot**. Hook the needle onto the strip on the left side. Place your finger under the place where the two strips are connected. Wrap the strip with the needle around your finger and over the other strip, Figure 4. Thread the needle through the loop you made.

Figure 4: Making the first knot

4. **Make a several knots**. Take one tail of the strip and pull it through the first loop. It's similar to crochet, but you use your needle rather than a hook. Repeat this process through the loop you just made until you have four or five loops, as shown in the Figure 5.

Figure 5: Making several knots

5. **Make a circle**. Bring the first knot next to the last making a circular. The tail with the needle should be on the left side and the other tail on the right side. The right tail is crossed with the first knot, the needle put through the hole of the first knot. Join the first and the last knot in the circle. Keep doing that round and round, Figure 6.

Figure 6: Making a circle

6. **Finish your rug.** Turn the rug inside out. Tie the two ends of the strips together, and thread the excess through the loops, Figure 7.

Figure 7: Finishing the rug

4. CONCLUSION

Traditional textile processes are an invaluable resource for tackling contemporary environmental and social issues. Among them, the knotting process stands out as a simple, accessible, and ecological approach for effectively reusing textile waste while producing long-lasting and practical items. Its capacity to repurpose unwanted materials into useful things like rugs, bags, baskets, and humanitarian supplies proves its practical relevance in the context of a circular economy. The technique involves few materials, can be learnt quickly, and is appropriate for individuals of all ages and skill levels, making it a viable approach for community-based initiatives, educational programs, and humanitarian efforts.

Furthermore, knotted items are long-lasting, repairable, and adaptable to a variety of applications, helping to reduce resource consumption and lengthen product life cycles.
The workshop activities presented in this paper confirmed that traditional textile knowledge can successfully be integrated into modern sustainability practices. By combining creativity, environmental responsibility, and social engagement, the knotting technique contributes not only to reducing textile waste but also to strengthening community resilience and supporting vulnerable populations.
Therefore, the revival and wider application of traditional knotting techniques can play an important role in promoting sustainable textile production, preserving cultural heritage, and developing practical solutions for future environmental and humanitarian needs.

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TEXTILE INDUSTRY OF LESKOVAC IN TOURIST POSTCARDS

Professional paper
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ABSTRACT: *In this paper, the author examines the representation of textile factories from Leskovac and its surrounding area on tourist postcards. Tourist postcards were once highly popular both in Serbia and worldwide; however, with the development of electronic communication technologies in recent decades, they have been largely pushed into the background. Nevertheless, in recent years there has been a renewed interest in sending and collecting postcards, indicating a revived cultural and tourism value of this medium. Tourist postcards play an important role in presenting the natural, cultural, and industrial characteristics of specific areas, contributing to the promotion of tourist destinations and the preservation of collective memory. Special emphasis in this paper is placed on postcards featuring motifs of textile factories in Leskovac and its surroundings. Numerous old postcards depicted textile factories, thereby representing the city known as the "Serbian Manchester," due to its once highly developed textile industry. The paper briefly describes the types of tourist postcards that were once produced in Leskovac, as well as their contemporary forms of production. Special attention is given to the importance of preserving postcards related to the textile industry and ethnological motifs of this region of Serbia as part of cultural and industrial heritage. The empirical part of the study is based on a survey conducted among adult respondents. The research analyzes respondents' attitudes toward tourist postcards and textile factories, as well as their perception of the interrelation between them. The obtained results are presented and analyzed using statistical methods, including tabular and graphical representation of relative values.*

Keywords: *textile industry, tourist postcards, textile factories, industrial heritage, Leskovac.*

TEKSTILNA INDUSTRIJA LESKOVCA NA TURISITČKIM RAZGLEDNICAMA

APSTRAKT*: U ovom radu autor se bavi predstavljanjem tekstilnih fabrika iz Leskovca i okoline na turističkim razglednicama. Turističke razglednice nekada su bile veoma popularne, kako u Srbiji tako i širom sveta, dok su sa razvojem elektronskih komunikacija u poslednjim decenijama potisnute u drugi plan. Ipak, u novije vreme ponovo raste*

interesovanje za njihovo slanje i sakupljanje, što ukazuje na obnovljenu kulturnu i turističku vrednost razglednica. Turističke razglednice imaju značajnu ulogu u predstavljanju prirodnih, kulturnih i industrijskih obeležja određenih područja, doprinoseći promociji turističkih destinacija i očuvanju kolektivnog pamćenja. Poseban akcenat u radu stavljen je na razglednice sa motivima tekstilnih fabrika u Leskovcu i njegovoj okolini. Na brojnim starim razglednicama prikazivane su tekstilne fabrike, čime je predstavljan grad poznat pod epitetom „Srpski Mančester“, zahvaljujući nekada izuzetno razvijenojtekstilnoj industriji. U radu su ukratko opisane vrste turističkih razglednica koje su se nekada izrađivale u is Leskovcu, kao i savremeni oblici njihove produkcije. Posebna pažnja posvećena je značaju očuvanja razglednica povezanih sa tekstilnom industrijom i etnološkim motivima ovog područja Srbije, kao dela kulturnog i industrijskog nasleđa. Empirijski deo rada zasniva se na anketnom istraživanju sprovedenom među punoletnim ispitanicima. Istraživanjem su analizirani stavovi ispitanika o turističkimrazglednicama i tekstilnim fabrikama, kao i percepcija njihove međusobne povezanosti. Dobijeni rezultati prikazani su i analizirani primenom statističkih metoda, uztabelarni i grafički prikaz relativnih vrednosti.

Ključne reči: *tekstil, turističke razglednice, tekstilne fabrike, industrijsko nasleđe, Leskovac.*

1. INTRODUCTION

Tourist postcards represent an important form of visual communication and one of the most recognizable souvenirs of tourist destinations. For more than a century, they have served as a means of transmitting messages, as well as a way of presenting the natural, cultural, historical, and economic values of specific areas. In addition to their communicative function, postcards today have significant documentary value, as they testify to the appearance of settlements, economic activities, architecture, and social conditions of the period in which they were created. With the development of modern information and communication technologies and digital forms of communication, the use of tourist postcards has significantly declined. However, in recent years there has been a renewed interest in their collection, study, and use in tourism promotion. Postcards have become an important historical source that enables the reconstruction of the past and the preservation of collective memory within local communities. Industrial facilities and economic complexes occupy a special place among motifs on tourist postcards. Their representation on postcards indicates the importance of industry in the economic and social development of individual cities. In this context, Leskovac represents a particularly interesting example. Thanks to the strong development of the textile industry during the first half of the 20th century, the city earned the nickname “Serbian Manchester” and became one of the most important industrial centers in Serbia. Numerous textile factories, production plants, and industrial complexes were frequent motifs on tourist postcards, which simultaneously

represented the city and its economic strength. The subject of this paper is tourist postcards featuring motifs of the textile industry of Leskovac and its surroundings. The aim of the study is to highlight the importance of these postcards as testimonies of the city's industrial development, as well as their potential as a means of preserving and promoting industrial heritage in the function of tourism development. Special attention is given to the analysis of postcards depicting textile factories, as well as to examining public attitudes regarding their significance and connection with the tourism offer. The research uses content analysis of tourist postcards, the descriptive method, and a survey conducted among adult respondents. The obtained results were processed using appropriate statistical methods and presented in tables and graphs. The findings may contribute to a better understanding of the role of tourist postcards in preserving industrial heritage and its contemporary tourism valorization.

1.1. Subject and Aim of the Research

The subject of this research consists of tourist postcards featuring motifs of the textile industry of Leskovac and its surroundings, as well as their significance in preserving and presenting industrial heritage. Special attention is given to postcards depicting textile factories, production complexes, and other facilities that testify to the economic development of Leskovac during the period of the most intensive growth of the textile industry. The research is based on the assumption that tourist postcards represent a valuable historical and documentary source, enabling insight into the appearance and importance of industrial facilities in the past. At the same time, they may play an important role in contemporary processes of cultural and industrial heritage preservation, as well as in promoting the tourism values of the local community. Sustainability is based on the principles of the long-term and stable functioning of its components, which do not generate errors or cause harm, thereby contributing to the efficient and effective achievement of process outcomes [1]. The main aim of the paper is to analyze tourist postcards with motifs of the textile industry of Leskovac and determine their significance as testimonies of the city's industrial development and as a potential tool for tourism promotion. A specific objective is to examine the attitudes of adult respondents regarding tourist postcards, textile factories, and their interrelation in the context of industrial heritage preservation.

1.2. The Importance of Tourist Postcards in Promoting Tourist Destinations

Tourist postcards are one of the oldest and most widespread visual media in the promotion of tourist destinations. Their primary function is the presentation of space, natural and cultural values, and specific characteristics of a place in a concise and visually attractive manner. Thanks to the combination of image and short message, postcards have played an important role in shaping the tourist image of destinations. In addition to their promotional role, tourist postcards also have an important communicative and documentary function. They enable the dissemination of information about destinations over wide geographic areas, contributing to their recognition and attractiveness among potential tourists. At the same time, postcards often become visual symbols of places, influencing the formation of destination identity. In contemporary conditions, although digital media dominate tourism

promotion, postcards retain their value as a traditional and authentic form of representation [2]. They are increasingly regarded as part of cultural heritage and as collector's items, which further enhances their significance in tourism valorization. Due to their long-term use and visual recognizability, tourist postcards remain an important instrument in the preservation and promotion of tourism values, especially when used to represent specific thematic areas such as industrial or cultural heritage.

1.3. Research Methodology

This study applies a multi-methodological approach combining qualitative and quantitative research methods. The theoretical part is based on the analysis of relevant scientific literature and available tourist postcards featuring motifs of the textile industry of Leskovac. The qualitative approach includes content analysis of postcards, focusing on visual and thematic elements, particularly representations of textile factories and industrial facilities. The descriptive method is also used to examine the historical and social context of textile industry development in Leskovac. The quantitative part is based on a survey conducted among adult respondents. The questionnaire included closed and semi-open questions aimed at examining attitudes toward tourist postcards, the importance of the textile industry, and their interrelation in tourism promotion [3]. Collected data were processed using statistical methods and presented in tables and graphs.
General hypothesis: Tourist postcards featuring motifs of the textile industry of Leskovac represent an important medium for preserving industrial heritage and may contribute to its contemporary tourism promotion and valorization.

2. TOURIST POSTCARDS AS PART OF CULTURAL AND TOURISM HERITAGE

This chapter discusses tourist postcards as an important part of cultural and tourism heritage, with special emphasis on their historical development, typology, and role in contemporary tourism communication [4]. Postcards represent a specific visual medium that has played an important role in presenting space, cultural values, and economic activities [5]. Figure 1 shows a tourist map of the city of Manchester, England, from the early 20th century, showing textile factories.

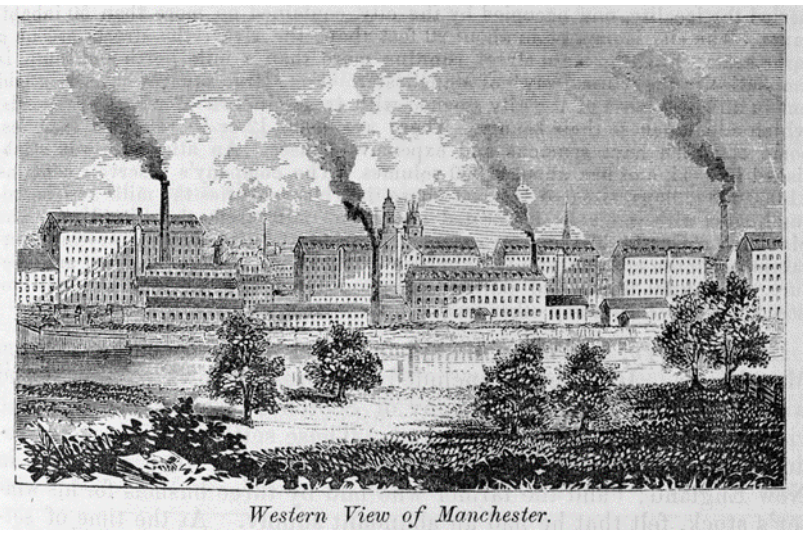

Figure 1: Old postcard – Mancheser in England

2.1. Historical Development of Tourist Postcards

Tourist postcards emerged in the second half of the 19th century during the intensive development of postal services, photography, and early mass tourism. Their origin is linked to the need for fast and simple communication, as well as the desire to visually present distant places and destinations. Initially, postcards were simple in design, often monochromatic and with limited visual elements [6]. With the development of printing techniques, especially lithography and later offset printing, their quality significantly improved. The introduction of color postcards in the 20th century contributed to their popularity, making them one of the most widespread tourist souvenirs [7]. The first half of the 20th century represents the “golden age” of postcards, when they were used not only for tourism but also as a means of personal communication. In that period, postcards became an important medium for presenting cities, landscapes, architecture, and industrial facilities. With the development of digital technologies in the second half of the 20th and early 21st century, their use declined, but they gained new roles as collectible items, museum exhibits, and cultural-historical sources.

2.2. Types and Characteristics of Tourist Postcards

Tourist postcards can be classified according to content, production technique, and function. Based on content, they include natural landscapes, urban spaces, cultural monuments, ethnographic motifs, and industrial facilities. According to production technique, they are divided into photographic, illustrated, and combined postcards. Photographic postcards provide realistic visual documentation, while illustrated postcards emphasize artistic interpretation. The absorbency of textile materials represents one of the most significant properties contributing to the comfort of textiles intended for widespread

use [8]. Combined postcards integrate photographs, graphics, and textual information. A key characteristic of postcards is their ability to convey destination identity in a limited format, making them an effective promotional tool.

2.3. Role of Postcards in Tourism Promotion and Cultural Heritage Preservation

Tourist postcards play a multiple role in tourism communication, including promotional, informational, and documentary functions. They enable fast presentation of destinations and contribute to their visibility and attractiveness. They also serve as “visual ambassadors” of destinations and are important sources for cultural and historical research, enabling reconstruction of urban and social development. In modern conditions, postcards retain their value as part of cultural heritage and as tools for interpreting local identity, particularly in the context of industrial heritage [9].

3. DEVELOPMENT OF THE TEXTILE INDUSTRY IN LESKOVAC

The development of the textile industry in Leskovac represents one of the most significant segments of the economic history of southern Serbia. Due to its favorable geographical position, developed trade, and entrepreneurial spirit of the local population, Leskovac grew during the 19th and first half of the 20th century into one of the leading industrial centers in the region. Textile production became the foundation of the city’s economic development and an important factor in its urbanization and modernization.

3.1. Beginnings and Development of the Textile Industry in Leskovac

The beginnings of textile production in Leskovac date back to the end of the 19th century, when craft production gradually transformed into early industrial production. Initially, small workshops and family enterprises dominated, producing fabrics, yarn, and various textile products. The development of trade relations and the emergence of the first mechanized facilities enabled faster industrialization and expansion of production.

During the first half of the 20th century, the textile industry in Leskovac experienced significant growth. Larger factories were established, modern machines were introduced, and production capacity increased. The city became known for the quality of its textile products, and its industry gained regional and national importance. This period represents a key phase in shaping the industrial identity of Leskovac.

3.2. Leskovac as “Serbian Manchester” – Historical and Economic Context

Leskovac is often referred to in domestic and foreign literature as “Serbian Manchester,” highlighting its exceptional importance in the field of textile industry. This name originates from the period when the city, similar to Manchester in England, was strongly industrialized and focused on textile production as its dominant economic sector. Industrial development was accompanied by rapid urbanization, population growth, and the formation of the working class. Textile factories were not only economic centers but also important social institutions influencing everyday life. In this context, Leskovac became a

recognizable industrial city whose identity was strongly linked to textile production. Figure 2 shows a old tourist postcard of Leskovac in Serbia, showing a textile factory.

Figure 2: Old postcard – Leskovac in Serbia

3.3. The Most Important Textile Factories and Their Contribution to Economic Development

The development of the textile industry in Leskovac was based on several major factories and industrial facilities that played a key role in the city's economic progress. These factories employed large numbers of workers and produced significant quantities of textile goods for domestic and international markets [10]. They also influenced the social structure of the city, the development of education, and the formation of industrial culture. Their existence contributed to infrastructure development, housing construction, and overall urban development of Leskovac. Although the textile industry declined in the late 20th century due to economic and transitional changes, its heritage remains an important part of the city's identity. Today, its potential is increasingly recognized in the context of industrial tourism and cultural valorization, particularly through historical sources such as tourist postcards.

4. TEXTILE FACTORIES ON TOURIST POSTCARDS

Tourist postcards featuring motifs of the textile industry in Leskovac represent an important visual and documentary source for studying the city's industrial development. They serve not only as a means of tourism promotion but also as valuable historical

material enabling reconstruction of industrial facilities, urban space, and the economic strength of Leskovac during its most intensive industrial development.

4.1. Analysis of Visual Motifs and Depictions of Textile Factories

Visual analysis of tourist postcards shows that textile factories were frequently presented as representative symbols of Leskovac's industrial strength. Postcards commonly depict factory buildings, chimneys, production halls, and industrial complexes within urban or semi-urban landscapes [11]. The representation depended on the period of origin. Older postcards emphasize monumentality and industrial significance, while newer ones tend toward a more documentary and realistic photographic approach. In both cases, factories are presented as symbols of progress, modernization, and economic power [12]. Industrial facilities were often placed in the foreground of the composition, emphasizing their central role in the identity of Leskovac as an industrial center. Picture 3 shows the old touristic map of the town of Leskovac in Serbia, on which many textile factories with their chimneys can be seen in the background [13].

Figure 3: Old postcard – Leskovac in Serbia

4.2. Tourist Postcards as Documentary Evidence of Industrial Development

Tourist postcards represent a valuable documentary source for studying the industrial development of Leskovac. They provide visual data on factory appearance, infrastructure, and urban space in different historical periods. In the absence of systematic photographic and archival documentation, postcards often serve as the only or supplementary source for

reconstructing the city's industrial past. Beyond architectural characteristics, postcards also testify to the economic importance of the textile industry, which was a driving force of Leskovac's development during the 19th and 20th centuries. In this way, postcards transcend their tourist function and become an important historical source enabling interdisciplinary research in history, tourism, cultural studies, and industrial heritage. Picture 4 shows the old tourist information centre in the town of Leskovac in Serbia, with the fair building visible. This building, called Šajkača, after the famous Serbian hat, has hosted many international textile fairs.

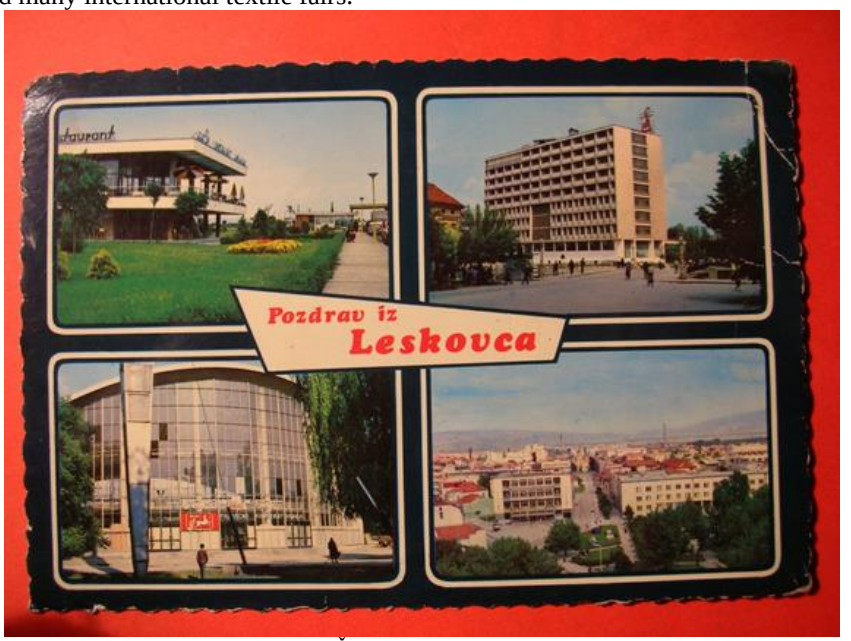

Figure 4: Old postcard –the Šajkača building, the international textile fair

4.3. Importance of Industrial Postcards in Tourism and Cultural Valorization

Postcards with industrial motifs are increasingly significant in contemporary tourism and cultural valorization processes [14]. Industrial heritage, long neglected in tourism offerings, is now recognized as an important resource for cultural and urban tourism development. In this context, tourist postcards serve as a medium for interpreting industrial history and making it accessible to the wider public. They contribute to awareness of industrial heritage and its role in shaping local identity [15]. They also have an educational function and can be used in museum exhibitions, displays, and tourist presentations as visual evidence of historical development. Modern tourism trends, which increasingly integrate industrial heritage into tourism products, further enhance the importance of such postcards, connecting past and present development. Picture 5 shows a tourist postcard and a building in Vučje near Leskovac. The building is known as the Teokarevic villa, named after one of the great textile industrialists of the early 20th century.

Figure 5: Old postcard – the Teokarevic villa, Vučje near Leskovac

5. RESULTS OF THE SURVEY RESEARCH

The empirical part of the study is based on a survey conducted among adult respondents. The aim was to examine attitudes toward tourist postcards, the importance of the textile industry in Leskovac, and perceptions of their interconnection in the context of tourism valorization of industrial heritage [16]. The total sample included 100 respondents of different gender, age, and educational background. Data were analyzed using descriptive statistical methods and presented in tables and graphs.

5.1. Structure and Characteristics of the Sample

The sample was evenly distributed by gender and age groups, ensuring relevant interpretation of results.

Gender structure of respondents

- Men: 48%
- Women: 52%

Age structure of respondents

- 18–30 years: 35%
- 31–50 years: 40%

- 51+ years: 25%

The sample shows a predominance of middle-aged respondents, contributing to the relevance of attitudes toward the research topic.

5.2. Analysis of Attitudes Toward Tourist Postcards

Results show that most respondents have a positive attitude toward tourist postcards as a cultural and tourism medium.

- 72% consider postcards to have cultural and historical value
- 18% see them as an outdated form of communication
- 10% have no clear opinion

Additionally, 64% stated they would use or collect postcards again if they were thematically modernized.

5.3. Attitudes Toward the Importance of the Textile Industry in Leskovac

Results indicate that respondents recognize the importance of the textile industry in the historical development of the city.

- 80% consider it a key factor in Leskovac’s development
- 12% partially agree
- 8% do not recognize its significance

5.4. Perception of the Connection Between Postcards and Industrial Heritage

- 68% believe there is a strong connection
- 22% see a partial connection
- 10% see no significant connection

Furthermore, 61% believe that industrial postcards could be an important part of the city’s tourism offer.

5.5. Discussion of Results

The results indicate a high level of awareness regarding the importance of the textile industry in Leskovac’s historical development, as well as a positive attitude toward tourist postcards as a cultural medium. Most respondents recognize the potential of integrating industrial heritage into tourism promotion. This suggests opportunities for developing new tourism products based on industrial heritage, including thematic postcards, exhibitions, and museum displays [17]. The results confirm the initial hypothesis that tourist postcards featuring motifs of the textile industry represent an important medium for preserving and promoting industrial heritage and may contribute to its tourism valorization.

6. POSSIBILITIES FOR VALORIZATION OF TEXTILE HERITAGE IN TOURISM

Industrial heritage is increasingly recognized as a valuable resource in contemporary cultural and urban tourism development. In this context, the textile industry of Leskovac, which played a key role in the city’s economic and social development, is increasingly seen as an important part of local cultural identity.

6.1. Industrial Heritage as a Resource for Cultural and Industrial Tourism Development

Industrial heritage includes both tangible and intangible traces of industrial development, such as factory buildings, infrastructure, technological systems, and cultural patterns of working-class life. Leskovac possesses significant potential for industrial tourism development. Former factories and industrial complexes can be interpreted as tourist attractions, contributing to diversification of the city's tourism offer. Valorization involves protection, presentation, and integration of industrial heritage into tourism flows.

6.2. Role of Tourist Postcards in Interpreting Industrial Heritage

Tourist postcards are an important medium for interpreting industrial heritage, enabling visual representation of historical structures and processes. Postcards of textile factories in Leskovac have documentary value as they depict industrial complexes at the height of their development. They enable reconstruction of industrial history and contribute to understanding the role of textile production in shaping urban and economic identity. They also serve an educational purpose in museums, exhibitions, and tourism presentations.

6.3. Guidelines for Improving Tourism Offer Based on Industrial Heritage

The development of Leskovac's tourism offer can be improved through integration of industrial heritage into tourism products. One approach is the creation of thematic industrial heritage routes including former factories, museum exhibitions, and cultural sites. The development of thematic souvenirs, especially modern postcards with historical factory motifs, can enhance local identity and tourism attractiveness. Additionally, exhibitions, digital archives, and educational programs can improve visibility and understanding of industrial heritage. By involving the local community and institutions, sustainable development models can be created based on preservation and promotion of industrial heritage.

7. CONCLUSION

Based on theoretical analysis and empirical research, it can be concluded that tourist postcards featuring motifs of the textile industry represent an important segment of the cultural and historical heritage of Leskovac. They document industrial development and urban space, while also serving as a medium for interpreting the past and promoting local identity.

Survey results show that respondents largely recognize the importance of the textile industry and the cultural value of postcards. Most support linking industrial heritage with tourism development. The findings indicate potential for contemporary tourism valorization through thematic postcards, exhibitions, and educational content. The initial hypothesis has been fully confirmed.

Tourist postcards, although a traditional medium, remain relevant today through their role in preserving cultural memory and promoting industrial heritage. Leskovac has significant potential for further development of cultural and industrial tourism based on these resources.

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SESSION VI

LEATHER AND FOOTWEAR

MATERIAL QUALITY ANALYSIS OF GARMENT LEATHERS FOR SUSTAINABLE LEATHER AND FOOTWEAR DESIGN

Scientific paper
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ABSTRACT: *Leather is a widely used material in the garment and footwear industry due to its durability, flexibility, aesthetic appeal, and comfort. The performance of leather products largely depends on the intrinsic properties of the raw material and the finishing techniques applied. This study focuses on the quality characterization of different types of garment leathers with reference to their suitability for sustainable leather and footwear design. Various leather types, including cowhide, sheepskin, lambskin, and goatskin, along with different finishing techniques such as aniline, semi-aniline, pigmented, nubuck, and suede, were evaluated. Standard physical performance tests, including colour fastness, tear strength, tensile strength, thickness, and water repellency, were conducted to assess their quality characteristics. The results indicate that pigmented leather exhibits superior colour fastness and water repellency, making it suitable for applications requiring high durability and environmental resistance. In contrast, aniline leather shows lower resistance to environmental factors but offers better aesthetic appeal. Among the leather types studied, cow nubuck leather demonstrates the highest thickness, tensile strength, and tear resistance, indicating superior mechanical performance, while lamb nappa leather provides enhanced softness and comfort for premium applications. The study highlights that finishing processes significantly influence surface-related properties, whereas intrinsic fibre structure governs mechanical performance. These findings provide valuable insights for selecting appropriate leather materials for specific garment and footwear applications, contributing to improved product performance and sustainable design practices.*

Keywords: *Leather quality characterisation, Garment and footwear applications, Leather finishing technique, Mechanical properties of leather, Sustainable leather design.*

ANALIZA KVALITETA MATERIJALA OD KOŽE ZA ODRŽIVI DIZAJN KOŽE I OBUĆE

APSTRAKT: *Koža je široko korišćeni materijal u industriji odeće i obuće zbog svoje izdržljivosti, fleksibilnosti, estetske privlačnosti i udobnosti. Performanse kožnih proizvoda u velikoj meri zavise od suštinskih svojstava sirovine i primenjenih tehnika završne obrade. Ova studija se fokusira na karakterizaciju kvaliteta različitih vrsta kože za odeću u odnosu na njihovu pogodnost za održivi dizajn kože i obuće. Procenjene su različite vrste kože, uključujući kravlju, ovčiju, jagnjeću i kozju kožu, zajedno sa različitim tehnikama završne obrade kao što su anilin, poluanilin, pigmentirana, nubuk i velur. Standardni testovi fizičkih performansi, uključujući postojanost boje, čvrstoću na kidanje, zateznu čvrstoću, debljinu i vodoodbojnost, sprovedeni su kako bi se procenili njihovi kvalitetni karakteristike. Rezultati pokazuju da pigmentirana koža pokazuje superiornu postojanost boje i vodoodbojnost, što je čini pogodnom za primene koje zahtevaju visoku izdržljivost i otpornost na uticaje okoline. Nasuprot tome, anilinska koža pokazuje manju otpornost na faktore okoline, ali nudi bolju estetsku privlačnost. Među proučavanim tipovima kože, goveđa nubuk koža pokazuje najveću debljinu, zateznu čvrstoću i otpornost na kidanje, što ukazuje na superiorne mehaničke performanse, dok jagnjeća napa koža pruža poboljšanu mekoću i udobnost za premium primene. Studija ističe da procesi završne obrade značajno utiču na površinska svojstva, dok unutrašnja struktura vlakana upravlja mehaničkim performansama. Ovi nalazi pružaju vredne uvide za izbor odgovarajućih kožnih materijala za specifične primene u odeći i obući, doprinoseći poboljšanim performansama proizvoda i održivim praksama dizajna.*

Ključne reči: *Karakterizacija kvaliteta kože, Primena u odeći i obući, Tehnika završne obrade kože, Mehanička svojstva kože, Održivi dizajn kože.*

1. INTRODUCTION

Leather is a versatile and durable material widely used in the garment industry due to its strength, flexibility, and softness. It is a biological material derived from animal hides and skins and converted into a stable product through chemical treatment known as tanning. Raw materials include hides from large animals such as cows and horses and skins from smaller animals such as sheep, goats, pigs, and calves. In the leather industry, the term *hides* refers to skins from larger animals, while *skins* refer to those from smaller animals. Animal hides consist of three structural layers: epidermis, corium, and flesh layer. Among these, the corium layer is most important for leather production because it contains collagen fibres that provide strength and durability to the material [1].

Leather manufacturing involves several important steps, including cleaning, tanning, retanning, milling, and finishing. During cleaning, impurities such as hair, dirt, and fats are removed from raw hides. Tanning stabilizes the collagen fibres using chemical agents, making the material resistant to decomposition, moisture, and microorganisms. Retanning improves leather quality through dyeing and fat liquoring, while milling enhances softness. Finally, finishing processes such as dyeing, coating, waxing, embossing, and oiling improve the appearance and performance of leather [2].

Different types of leather are produced depending on the raw material source, manufacturing process, and finishing treatments. Common leathers used in garment manufacturing include cowhide, sheepskin, lambskin, and goatskin, each possessing properties such as strength, softness, breathability, and flexibility. Finishing methods such as aniline, semi-aniline, pigmented, suede, and nubuck finishes enhance visual appearance and influence properties such as colour fastness, abrasion resistance, softness, and water resistance, which are important for garment applications [3].
Maintaining leather quality is essential in the garment industry to ensure durability and functionality. Quality characterization is performed through physical and chemical tests such as tensile strength, tear strength, thickness measurement, colour fastness, and water repellency tests to evaluate the performance and suitability of leather materials [4]. Therefore, this study focuses on the quality characterization of different types of leather used in the garment industry by evaluating their physical properties to obtain a comparative understanding of their performance characteristics.

2. MATERIALS AND METHODS

2.1 Leather Manufacturing Process

- Cleaning: Animal hides and skins are preserved using salt or refrigeration during transportation to prevent microbial degradation. During cleaning, impurities such as dirt, hair, residual salts, and excess fats are removed through degreasing. This stage, also known as wet processing, prepares the hides for further treatment and the cleaned hides are graded into categories such as full grain leather, top grain leather, nubuck leather, and suede leather.
- Tanning: Tanning stabilizes the collagen fibres present in animal hides, improving resistance to microbial attack, environmental degradation, and chemical reactions. Common tanning methods include chrome tanning, vegetable tanning, and chrome-free tanning. Chrome-tanned leather is known as wet-blue leather, while leather processed without chrome is referred to as wet-white leather (Walton).
- Retanning: Retanning determines the final characteristics of leather. Dyeing is carried out to impart colour, and fat liquoring improves softness, flexibility, and fullness. Leather obtained after this stage is called crust leather, and the process helps modify leather properties according to applications such as garments, footwear, and upholstery [2].
- Milling: Milling is a mechanical treatment used to soften leather and enhance the natural grain structure. Leather is placed in rotating drums where the tumbling action improves softness and produces a natural grainy texture.
- Finishing: Finishing is the final stage of leather manufacturing. Processes such as dyeing, coating, waxing, oiling, and embossing are applied to improve the aesthetic appearance, durability, colour uniformity, and resistance to environmental factors of leather products [5].

2.2 Types of Leather

Different types of leather are used in the garment industry depending on the animal source and the properties required for specific applications. Each type possesses unique characteristics such as softness, durability, flexibility, and texture [6].

- **Cowhide Leather:** Cowhide leather is strong, durable, and resistant to wear. Due to its thickness and rugged nature, it is widely used for jackets, belts, footwear, and bags. It is commonly preferred for garments that require higher durability, such as biker jackets.
- **Sheepskin Leather:** Sheepskin leather is lightweight, soft, and flexible. It provides excellent comfort and easily adapts to body shape over time. Because of its smooth texture and softness, it is widely used in garment manufacturing.
- **Lambskin Leather:** Lambskin leather is considered a luxury leather due to its extremely smooth surface and soft texture. It is commonly used in high-end garments, coats, and fashion accessories because of its superior softness and aesthetic appearance.
- **Goatskin Leather:** Goatskin leather contains natural lanolin, which gives it a smooth and soft texture. It is lighter than cowhide leather but offers good durability and flexibility. Its distinctive grain pattern makes it suitable for garments, bags, and footwear.

2.3 Types of Leather Finishes

Leather finishing processes significantly influence the appearance and performance characteristics of leather products. Common finishes include aniline, semi-aniline, pigmented leather, suede, and nubuck finishes [3].

- **Aniline Finish:** Aniline leather is produced using water-soluble dyes without heavy surface coatings. This finish preserves the natural grain structure and provides a soft, luxurious appearance, but it is more susceptible to staining and fading.
- **Semi-Aniline Finish**: Semi-aniline leather has a thin protective coating that improves resistance to stains and sunlight while maintaining the natural grain appearance.
- **Pigmented Leather**: Pigmented leather contains a thicker resin-based coating that provides better abrasion resistance and colour uniformity, although it reduces breathability.
- **Suede:** Suede leather is produced by buffing the inner surface of the hide to create a soft and velvety texture. It is widely used in gloves, footwear, and fashion accessories.
- **Nubuck:** Nubuck leather is produced by buffing the outer grain surface to create a fine velvety texture. Compared to suede, nubuck is stronger and more durable.

2.4 Testing of Leather

Quality testing of leather is essential to ensure that leather products meet industry standards and customer expectations. Both chemical and physical tests are conducted to evaluate the performance of leather materials.

- **Chemical Testing:** Certain chemicals used during leather processing may produce harmful compounds such as aromatic amines. According to EU REACH regulations,

the permissible limit for these chemicals in leather products is 30 mg/kg (Eui Kyung Roh).

- **pH Testing**: The pH value of leather indicates the acidity or alkalinity of the material and influences the durability of the finished product. Chromium-tanned leather generally has a pH range between 3.2 and 5.5 [7]
- **Chromium VI Testing**: Chromium VI is a harmful compound that may form during chrome tanning. International regulations restrict its concentration to less than 3 mg/kg in leather products to prevent allergic reactions.

3. RESULT AND DISCUSSION

3.1 Testing of Leather

Azo colourants used in leather dyeing may generate toxic aromatic amines. Since these compounds are carcinogenic, strict regulations have been established by the EU and other countries to ensure that leather products are free from such harmful substances.

3.2 Legal Limit for Chemical Properties of Leather

Restricted chemicals in leather products are specified in Appendix 10 of the EU REACH regulations. According to Annex XVII, the permissible limit for each aromatic amine in leather is 30 mg/kg. Leather products meeting this requirement can obtain an Eco-label. Chinese regulations set a stricter limit of 20 mg/kg for toxic substances.

3.3 Testing Methods

Restricted chemicals in leather are identified through extraction and chemical reaction methods using the following standards:

- Determination of aromatic amines extracted from azo colourants (EN ISO 17234-1:2010)
- Determination of 4-aminoazobenzene (EN ISO 17234-2:2011)

3.4 Testing Leather for pH Value

The pH value indicates the acidity or alkalinity of leather and influences the durability of the finished product. It also reflects the effectiveness of tanning and dyeing processes. pH can be measured either in solution or directly on the leather sample.

3.4.1 Testing Methods

pH testing can be performed using damp indicator paper for a quick estimate or by cutting the leather sample and measuring according to EN ISO 4045:2008 for accurate results. The pH scale ranges from 0–14:

- pH 1–7: Acidic
- pH 7: Neutral
- pH 8–14: Alkaline
- 3.4.2 Meaning of Test Results

Chromium-tanned leather normally has a pH range of 3.2–5.5. Excessive acidity may indicate poor tanning, leading to premature deterioration, whereas high alkalinity may cause improper dye fixation and colour fading.

3.5 Testing Leather for Chromium VI Compounds

Chromium (VI) may form during chrome tanning and can cause severe allergic reactions. Therefore, leather products sold in the EU must contain less than 3 mg/kg of Chromium VI.

3.5.1 Test Methods

The determination of Chromium (VI) content in leather is performed according to EN ISO 17075 using chemical extraction methods, followed by colorimetric or chromatographic analysis.

3.5.2 Meaning of Test Results

The Chromium (VI) content must not exceed 3 mg/kg (0.0003%) of the dry weight of leather when the pH is between 7.5 and 8.

3.6 Physical Tests for Leather

Physical tests simulate actual usage conditions to evaluate the durability and performance of leather products.

- Wetting Resistance (Spray Test): Evaluates the water repellency of the leather surface.
- Adhesive Properties of Finishing: Determines the adhesion of finishing layers on leather.
- Tear Load Test: Measures the force required to tear leather through two holes and assesses stitch tear resistance.
- Tensile Strength Test: Determines the load required to rupture leather using a 12.7 mm diameter specimen.
- Colour Fastness Test: Evaluates the resistance of coloured leather to washing and staining of adjacent fabrics.
- Relative Stiffness Test: Measures the stiffness of leather using a torsional apparatus.

3.7 Evaluation

Testing of leather products helps determine their quality and authenticity. Quality characterization ensures that leather meets the required standards for its intended application and confirms that the product satisfies consumer expectations.

3.8 Leathers used in Timberland Products

Timberland shoes and boots are mostly made of authentic leather. Timberland is a firm believer in natural leather and full grain because they feel that leather goods can improve

with age and last a long time. Pig, horse, horse, and cow hides were also used. They use a number of surface appearances, such as the ones mentioned below.

- Full grain (as it ages it is the best with patina)
- Nubuck is a type of leather that is used (a velvety premium suede look)
- Suede is a kind of suede that is (the bottom layer of the hide which is not as strong)
- Smooth finish with a smooth surface that contributes to the elegance and consistency of the surface.
- Milled leather is top grain leather that has been turned in a milling machine.

Quality Characterization of Leather in Timberland Products is shown in Table 1. Comparative Analysis of Quality Characterization of Leather in Timberland Products is indicated in Figure 1.

Table 1: Quality Characterization of Leather in Timberland Products

TESTS	PIGMENTED LEATHER	SEMI-ANILINE LEATHER	ANILINE LEATHER	NUBUCK AND SUEDE LEATHER
Colour fastness to light	4	4	2/3	4
Colour fastness to rubbing	Dry 3, Wet 2/3	Dry 3, Wet 2/3	Dry 3, Wet 2/3	Dry 3, Wet 2/3
Colour fastness to water spotting	3 (no residual halo)	3 (no residual halo)	3 (no residual halo)	3 (no residual halo)
Colour fastness to water	3	3	3	3
Colour fastness to dry cleaning	3 (no finish loss, no reoiling)	3 (no finish loss, no reoiling)	3 (no finish loss, no reoiling)	3 (no finish loss, no reoiling)
Tear strength	20 N	20 N	20 N	20 N
Water repellency	100	90	80	80

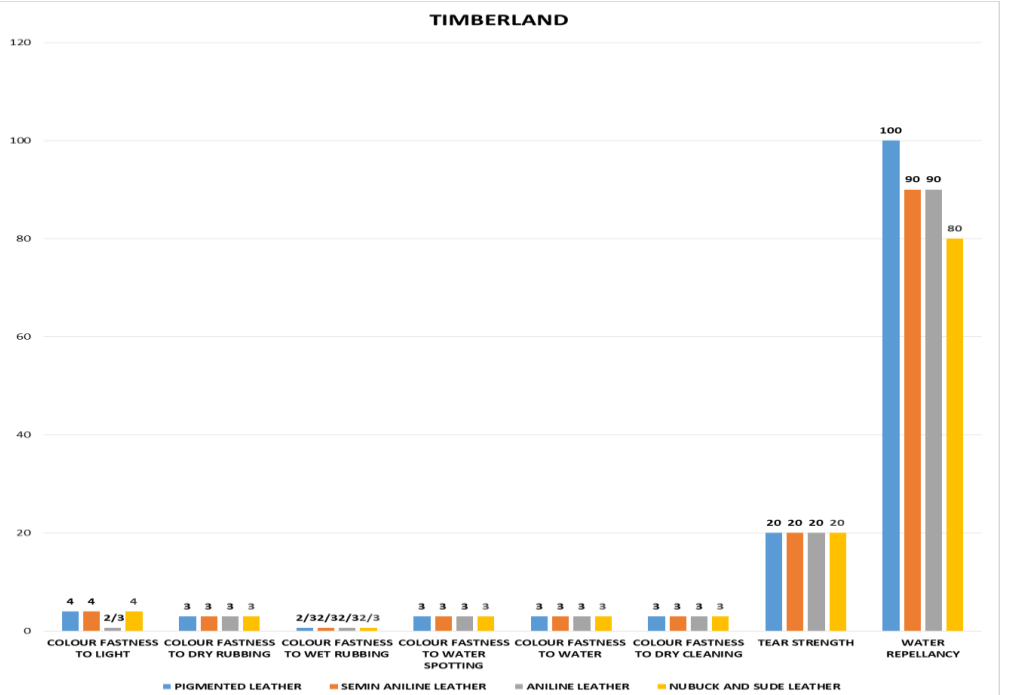

Figure 1: Comparative Analysis of Quality Characterization of Leather in Timberland Products

Table 1 presents the quality characterization of different leather finishes used in Timberland products, including pigmented, semi-aniline, aniline, and nubuck/suede leathers. It is observed that pigmented leather exhibits superior colour fastness to light (rating 4) and the highest water repellency (100%), indicating its enhanced resistance to environmental exposure. Semi-aniline leather also shows comparable colour fastness but slightly lower water repellency (90%). In contrast, aniline leather demonstrates relatively lower colour fastness to light (2/3), which can be attributed to the absence of protective surface coatings. All leather types exhibit similar performance in terms of tear strength (20 N) and colour fastness to rubbing, indicating that finishing primarily influences surface properties rather than mechanical strength.
Figure 1 further illustrates these trends, clearly showing that pigmented leather outperforms other finishes in durability-related properties, while nubuck and suede maintain moderate performance with aesthetic advantages.

3.9 . Leathers used in Tommy Hilfiger Products

Leathers products from Tommy Hilfiger are tested for its quality characteristics are Lamb nappa leather, Goat suede leather and Cow nubuck leather. Quality Characterization of Leather in Tommy Hilfiger Products is tabulated in Table 2. Comparative Analysis of Quality Characterization of Leather in Tommy Products is exhibited in Figure 2. Different types of leather products are given in Figure 3 (Cow Nubuck), Figure 4 (Goat Suede) and Figure 5 (.Lamb Nappa).

Table 2: Quality Characterization of Leather in Tommy Hilfiger Products

LEATHER & TESTS	THICKNESS	TONGUE TEAR STRENGTH ASTM D 4704	TENSILE STRENGTH ASTM D 2209
Lamb Nappa Leather	1.0 mm	5 to 6 lbf	20 to 30 lbf
Goat Suede Leather	0.9 mm	4 to 5 lbf	40 to 50 lbf
Goat Suede Leather	1.1 mm	6 to 7 lbf	60 to 70 lbf
Lamb Nappa Leather	0.7 mm	3 to 4 lbf	10 to 20 lbf
Cow Nubuck Leather	1.3 mm	10 to 15 lbf	70 to 90 lbf

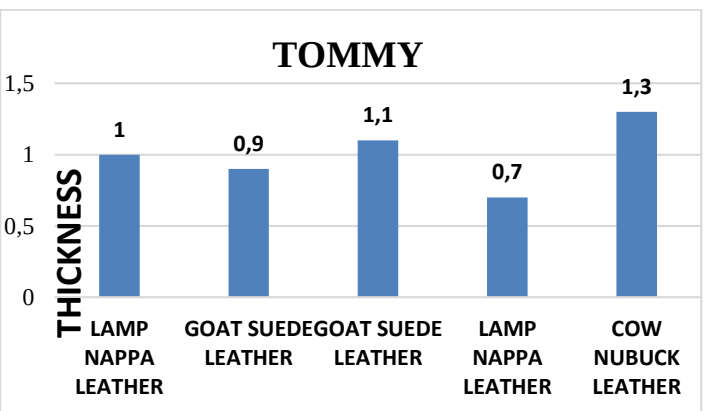

Figure 2: Comparative Analysis of Quality Characterization of Leather in Tommy Products

Figure 3: Cow Nubuck

Figure 4: Goat Suede

Figure 5: Lamb Nappa

Table 2 summarizes the physical and mechanical properties of different leather types used in Tommy Hilfiger products. Among the tested samples, cow nubuck leather exhibits the highest thickness (1.3 mm), tongue tear strength (10–15 lbf), and tensile strength (70–90 lbf), indicating superior structural integrity and durability. Goat suede leather shows moderate mechanical properties, with tensile strength ranging from 40 to 70 lbf depending on thickness, while lamb nappa leather demonstrates lower strength values (10–30 lbf) but offers better softness and flexibility, making it suitable for premium garment applications. Figure 2 provides a comparative visualization of these results, highlighting that mechanical performance increases with thickness and fibre compactness, with cow nubuck leather showing the best overall performance among the tested materials. Figures 3, 4, and 5 illustrate the surface characteristics of cow nubuck, goat suede, and lamb nappa leathers, respectively. Figure 3 (Cow Nubuck): Shows a fine, velvety surface with a dense fibre structure, which contributes to its high tensile and tear strength. Figure 4 (Goat Suede): Exhibits a softer and more porous structure due to buffing of the inner layer, resulting in moderate strength and enhanced flexibility. Figure 5 (Lamb Nappa): Displays a smooth and soft grain surface, characteristic of high-end garment leather, but with comparatively lower mechanical strength. These visual observations correlate well with the mechanical test results, confirming that surface structure and fibre compactness significantly influence the performance properties of leather materials.

The results indicate that finishing type strongly affects surface-related properties (colour fastness, water repellency), whereas intrinsic material structure governs mechanical properties (tensile and tear strength). Pigmented leather and cow nubuck leather emerge as the most suitable materials for applications requiring high durability, while aniline and lamb nappa leathers are more appropriate for aesthetic and comfort-oriented applications.

4. CONCLUSION

The quality is one of the most important characteristics that satisfy the customer’s expectations. Here we characterized the quality of the leather from Timberland and Tommy Hilfiger. Different kinds of leather from Timberland such as pigmented leather, aniline

leather, semi-aniline leather, nubuck and suede leather were characterised. The tests done for the quality characterization of these leathers were colour fastness, tear strength and water repellency. The pigmented leather has comparatively good water repellency and colour fastness than other leathers. Leathers products of Tommy Hilfiger were also characterized for its quality purpose and they are lamb nappa leather, goat suede leather and cow nubuck leather. The tests done for the quality characterization of these leathers were thickness, tongue tear strength ASTM D 4704 and tensile strength ASTM D 2209. The cow nubuck leather has comparatively good quality characteristics like thickness, tongue tear strength and tensile strength than other leathers. Hence, Timberland's pigmented leather and Tommy Hilfiger's cow nubuck leather has good quality parameter that satisfies the customer's expectations.

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INFLUENCE OF THREAD TYPE ON THE MECHANICAL PROPERTIES OF SEAMS IN FOOTWEAR

Scientific paper
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ABSTRACT: *The modern mass-produced footwear is made of textile, leather, plastic, and rubber parts all glued and sewn together. Textile materials are increasingly being used in the footwear industry. The mechanical properties of the seams used to join individual parts of the shoe upper affect the durability, flexibility and comfort of the footwear. This paper analyses the influence of polyester and polyamide threads of different fineness on the mechanical properties of the seams of the shoe upper made of laminated two-layer textile material. The results showed that the fineness and raw material composition of the thread, as well as the direction of cutting the upper parts, have a very important influence on the strength, elongation and flexibility of the seams, and thus of the shoe.*

Keywords: *footwear, thread, seams, mechanical properties.*

UTICAJ VRSTE KONCA NA MEHANIČKA SVOJSTVA ŠAVOVA U OBUĆI

APSTRAKT: *Moderna masovno proizvedena obuća izrađena je od tekstilnih, kožnih, plastičnih i gumenih dijelova, koji su svi lijepljeni i sašiveni zajedno. U industriji obuće se sve više koriste različiti tekstilni materijali. Mehanička svojstva šavova koji se koriste za spajanje pojedinih dijelova gornjišta obuće utiču na trajnost, fleksibilnost i udobnost obuće. U ovom radu je analiziran uticaj poliesterskih i poliamidnih konaca različite finoće na mehanička svojstva šavova gornjišta obuće izrađenog od laminiranog dvoslojnog tekstilnog materijala. Rezultati su pokazali da finoća i sirovinski sastav konca, kao i pravac iskrojavanja dijelova gornjišta imaju vema važan uticaj na trajnost i fleksibilnost šavova, a time i obuće.*

Ključne reči: *obuća, konac, šavovi, mehanička svojstva.*

1. INTRODUCTION

The modern way of life and work cannot be imagined without textile materials. Conventional applications include the use of textile materials for clothing and home textiles (various products used in the household). Today, textiles are used in all spheres of life. In addition to their application in the textile industry, textiles play a significant role in the footwear production. Textile materials of various types are widely used in footwear industry and play very important role in perfect shoe making [1]. The use of textile materials in shoes has been on the rise in recent years due to their numerous benefits [2-5]. Textile materials are more economic and more efficient way of replacing some costly traditional materials used to make footwear. Textile materials are lightweight, flexible and durable, providing a better fit and greater comfort [6]. Textile materials provide breathability, which helps to prevent the buildup of heat and moisture inside the shoe. With an infinite variety of weaves, colors, patterns, and special features, textiles have a special place in footwear design [7]. Blended and composite materials are also commonly used in textile materials for footwear [8]. Textile material is used almost in all parts of the footwear because the developments of various types of nonwoven fabric and other innovative forms textile. You will find textiles inside and out on footwear and even on the bottoms.
Today, there are many different methods for joining footwear parts, such as gluing and welding, but by far the most widely used method is the method of joining cut parts by sewing. A very important factor that affects the strength and flexibility of seams is the type of sewing thread. In the past, cotton thread was primarily used, but today polyester (PES) and polyamide (PA) threads are most often used. Therefore, this paper examines the influence of polyester and polyamide threads of different fineness on the mechanical properties of seams in footwear.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in the experimental work for the production of seams are commercially available polyester (PES) and polyamide (PA) threads for sewing footwear and laminated textile material for the production of footwear uppers. The designations and basic characteristics of the thread samples are shown in Table 1. The textile material for the footwear upper has a two-layer structure. The reverse side of the material is spunbond nonwoven made of polyester, while the top layer, which represents the face of the material, is a plain weave polyamide woven fabric.

Table 1: Thread samples used for experimental work

Sample code	Thread structure	Composition (%)	Fineness (tex)
PES300	Three-strand filament thread	100% PES	300
PES150	Three-strand filament thread	100% PES	150
PES75	Three-strand filament thread	100% PES	75
PA75	Three-strand filament thread	100% PA	75

2.1. Methods

The EN ISO 1833-1 standard was used for testing the material composition [9]. The longitudinal mass (fineness) of the thread was tested according to the EN ISO 2060 standard [10], while the breaking force and breaking elongation of the thread were tested according to the EN ISO 2062 standard [11]. The breaking force and breaking elongation testing procedure of textile materials for footwear uppers was carried out in accordance with the EN ISO 13934-1 standard [12] in the warp and weft directions, while the mass per unit area was determined according to the ISO 3801 standard [13].

Sample preparation and testing of breaking strength and breaking elongation of seams were carried out according to the EN ISO 13935-1 standard [14]. The samples were sewn on a universal sewing machine JUKI LZH-1290, with lock stitch type 301, with a density of 4 stitches/cm and a sewing needle of fineness Nm 90. In all samples, the seam was formed at a distance of 10 mm from the edge of the material.

For testing the breaking force and breaking elongation of the seam, 15 test samples were prepared for each tested thread, i.e. 5 test samples for making seams in three variants, when parts of the footwear upper are joined in the direction: warp/warp, weft/weft and warp/weft.

A Shimadzu universal dynamometer, type AUTOGRAPH AGS-X, was used for all breaking force and breaking elongation tests.

3. RESULTS AND DISCUSSION

The results of testing the physical and mechanical properties of textile materials for making uppers are shown in the Table 2.

Table 2: Physical and mechanical properties of textile materials for uppers

Mass per unit area (g/m^2)	Warp			Weft		
	Density (cm^{-1})	Breaking force (N)	Breaking elongation (%)	Density (cm^{-1})	Breaking force (N)	Breaking elongation (%)
425	14	2157	33	10	1917	40

The material used to make the upper has a high mass per unit area and high breaking force in both directions (warp and weft) because, due to its intended purpose, it needs to withstand forces and loads during use and ensure the durability of the product. The breaking force in the warp direction is greater than the breaking force in the weft direction, which is also influenced by the plain weave and the density of the fabric on the face of the material. The breaking elongation in the weft direction is greater than in the warp direction, which is common.

Figure 1. shows breaking force of thread samples. It is obvious that the breaking force depends on the fineness of the thread and decreases with increasing fineness [15]. The

breaking force of polyester (PES75) and polyamide (PA75) threads is not significantly different because both threads are synthetic and have the same fineness.

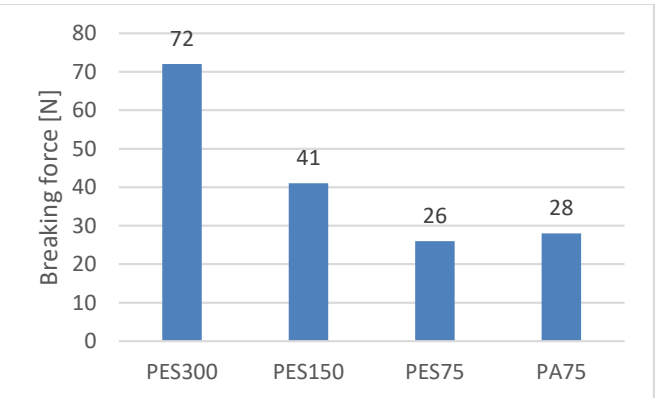

Figure 1: Breaking force depending on the type of thread

Figure 2. shows breaking elongation of thread samples. Unlike to the breaking force results, the polyester thread samples with higher fineness (PES150 and PES75) have higher breaking elongation compared to the PES300 thread sample, which has a significantly lower fineness. In addition, it is noticeable that the polyamide thread sample PA75 has the highest elongation at break (22.3%), significantly higher than all polyester thread samples.

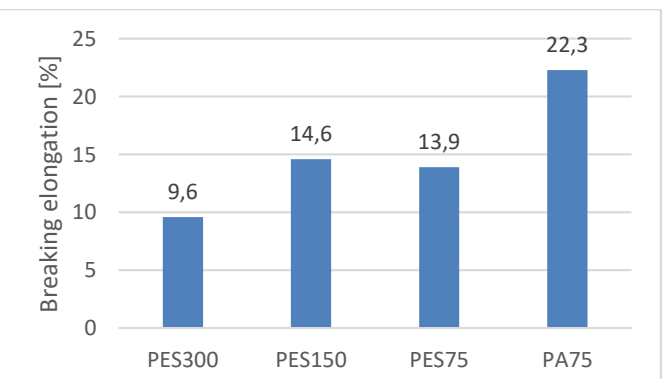

Figure 2: Breaking elongation depending on the type of thread

The dependence between seam breaking force and thread type for different cutting directions of footwear upper parts is shown in Figure 3.
The highest seam breaking force (1930 N) was obtained by sewing with PES300 thread and the cutting of the footwear upper parts in the warp/warp direction [15]. Sewing with

threads of lower breaking force (PES150 and PES75) results in lower seam breaking force (886 N and 621 N).
The influence of the cutting direction of the parts for the footwear upper on the seam breaking force is also significant. The highest seam breaking force is in the warp/warp direction, then warp/weft, and the lowest in the weft/weft direction for all thread sample.
Also, the breaking strength of a seam with polyamide thread PA75 is greater than a seam with polyester thread PES75.

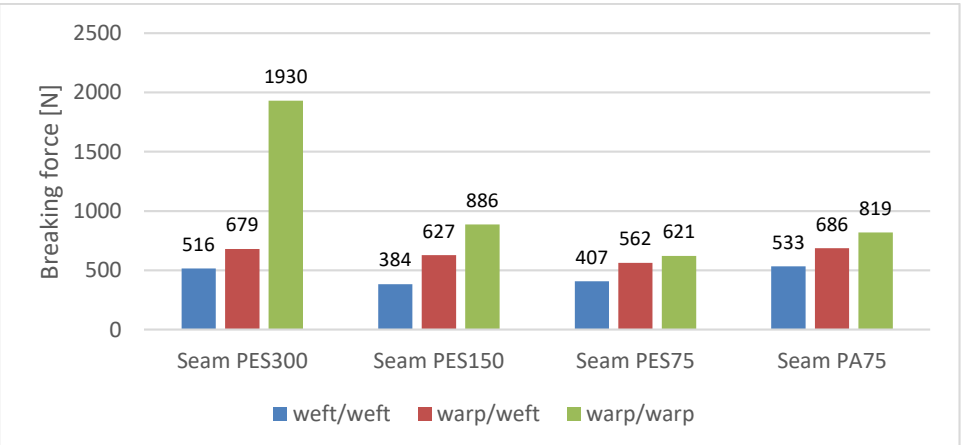

Figure 3: Comparison of seam breaking force on thread type for different cutting directions of footwear upper parts

The dependence between seam breaking elongation and thread type for different cutting directions of footwear upper parts is shown in Figure 4.
The highest seam breaking elongation (33,1 %) was obtained by sewing with PES300 thread and the cutting of the footwear upper parts in the warp/warp direction. However, the PES300 thread sample has the lowest elongation at break (Figure 2.). It is obvious that the material for the shoe upper and the direction of its cutting have a great influence on the breaking strength and breaking elongation. Similarly, sewing with threads of higher breaking elongation (PES150 and PES75) results in a lower breaking elongation of the seam. Also, the breaking elongation of a seam with polyamide thread PA75 is greater than that of a seam with polyester thread PES75.

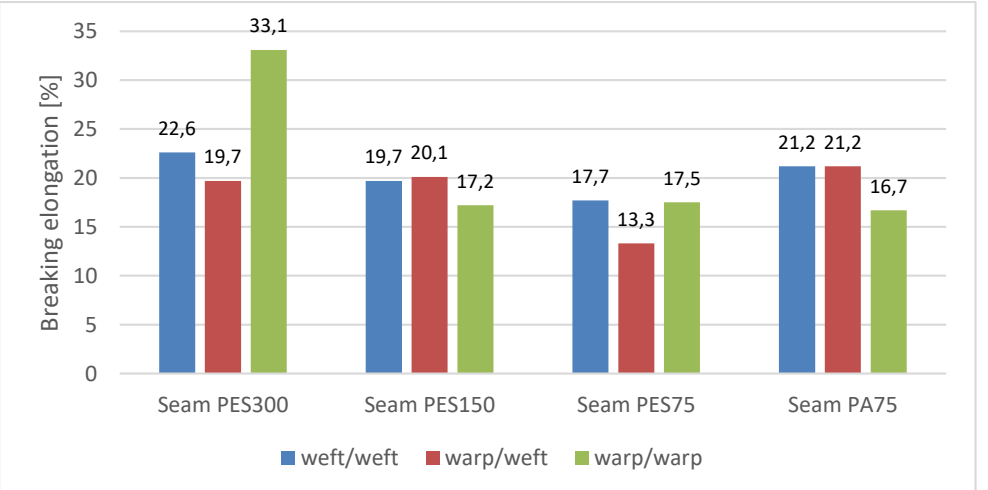

Figure 4: Comparison of seam breaking elongation on thread type for different cutting directions of footwear upper parts

4. CONCLUSION

Different types of textile materials are increasingly used in the footwear production. Textile parts are most often joined together by sewing, and the mechanical properties of the seam significantly affect the durability, flexibility and comfort of the footwear.

Based on the results obtained in this work, it can be concluded that the material composition, fineness and strength of sewing thread directly affect the breaking force and elongation of the seam. The strength of the seam decreases with increasing fineness of the thread used for sewing, meaning that threads with higher breaking force also produce a seam with higher breaking force. Also, using polyamide thread resulted in a seam (SeamPA75) with greater breaking force and elongation compared to a seam (SeamPES75) obtained by sewing with polyester thread of the same fineness.

The highest breaking force (1930 N) and breaking elongation (33.1%) of the seam (SeamPES300) were obtained using PES300 thread sample, which had the highest breaking force and the lowest elongation.

It is obvious that in addition to the thread, the material for the footwear upper and the direction of its cutting have a great influence on the breaking force of the seam and the breaking elongation of the seam.

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