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SUSTAINABLE TEXTILE WASTE MANAGEMENT AS AN ENGINEERING RESPONSE TO ENVIRONMENTAL PROTECTION CHALLENGES

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Abstract:
The textile sector is a significant source of environmental pressure due to high consumption of raw materials, water, and energy, as well as growing amounts of waste generated during the production, use, and disposal of textile products. This paper analyzes sustainable textile waste management as an engineering response to environmental protection challenges. Based on a review of relevant literature, the paper considers environmental pressures related to textile consumption, textile waste flows, key waste management approaches, and modern technological solutions for sorting and recycling. Special attention is given to automated sorting based on NIR spectroscopy and sensor-robotic systems, as well as to the role of eco-design and circular models in improving recyclability and material flow closure. The analysis indicates that sustainable textile waste management requires coordinated application of collection, sorting, recycling, and product design strategies.

Keywords: *Textile waste, sustainable management, recycling, NIR spectroscopy, circular economy*

Introduction

The textile sector has a significant economic role, but at the same time, it represents one of the most resource-intensive and environmentally burdensome production and consumption systems. At the global level, the sustainability of the textile value chain is increasingly viewed through the need to change consumption patterns, improve production and recycling practices, and invest more in infrastructure [1]. In review studies, textile waste is identified as one of the key open issues of the contemporary development of the textile industry, especially in the domain of collection, sorting, reuse, and recycling [2]. The growth of

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textile production and consumption was further fueled by the fast-fashion model, leading to an increase in textile waste and intensifying environmental pressure [3].

In the European Union, the average consumption of textiles increased from 17 kg per inhabitant in 2019 to 19 kg per inhabitant in 2022, with textile consumption associated with significant pressures on raw materials, water, soil, and climate [4, 5].

Table 1: *Environmental pressures associated with textile consumption in the EU in 2022*

Impact category	***Value (per person)***	***Description***
Emissions	355 kg	Greenhouse gas emissions associated with textile consumption
Primary raw materials	523 kg	The total amount of primary raw materials required for the production of textiles
Water consumption	12 m^3	Demand for water resources during the production and use of textiles
Land use	323 m^2	Land area connected to the entire textile supply chain

The data from Table 1 confirm that the textile sector represents an important target area in the transition to more circular models of production and consumption [4].

The problem of textile waste is further complicated by the heterogeneity of the material, the presence of mixed fibers, chemical additives, and complex structural solutions of the product, which complicates separate collection, precise sorting, and efficient recycling. For this reason, the sustainable management of textile waste cannot be reduced to disposal or subsequent processing, but also implies the connection of the waste hierarchy, modern technological approaches to the identification and separation of materials, appropriate recycling procedures, and eco-design principles [5].

This paper aims to analyze sustainable textile waste management as an engineering response to the challenges of environmental protection. The paper focuses in particular on environmental pressures associated with textile consumption, textile waste flows, modern technological approaches to sorting and recycling, as well as on the role of circular models and eco-design in improving the textile waste management system.

1. Textile waste and its impact on the environment

Textile waste includes materials generated in all stages of the textile product cycle, from production residues and unsold stocks to clothing after use and home textiles. In the literature, pre-consumer, post-consumer, and industrial textile waste are most often distinguished [3]. From the point of view of environmental engineering, the problem of textile waste is not only reflected in its physical volume, but also in the loss of energy, water, and raw materials incorporated into the product, which, after discarding, does not return to the production cycle [5].

According to the estimates of the European Environment Agency, the EU-27 generated about 6.95 million tons of textile waste in 2020, i.e., approximately 16 kg per inhabitant. Of that amount, 4.4 kg per inhabitant was collected for reuse and recycling, while 11.6 kg ended up in municipal waste. These data indicate the limited efficiency of the existing collection systems and confirm that the improvement of infrastructure, sorting, and technological solutions is one of the key prerequisites for more effective management of textile flows [6].

2. Technological approaches and engineering solutions in textile recycling

Sustainable management of textile waste implies the systematic application of engineering solutions in all stages of the process, from collection and sorting to reuse and recycling. The choice of the appropriate approach depends on the condition of the product, the fiber composition, the presence of additives and impurities, as well as on the final processing requirements. For this reason, textile flows cannot be directed by a single procedure, but it is necessary to apply a combination of technological and organizational solutions in accordance with the principles of waste hierarchy and circular economy [4].

Separate collection and sorting, reuse, mechanical recycling, and chemical recycling are distinguished in the literature as the basic approaches to sustainable management of textile waste [3, 4]. Separate collection and sorting play a key role as they determine the purity of the incoming streams and the possibility of further processing. Reuse extends the life of a product and is higher in the waste hierarchy than recycling, while mechanical and chemical recycling are applied when reuse is no longer possible or justified.

Table 2 summarizes key approaches to textile waste management, their purposes, advantages, and limitations [1, 3, 4].

Table 2: *Basic approaches to textile waste management*

Approach	*Purpose*	*Advantage*	*Limitation*
Separate collection and sorting	Separation of textiles according to condition and composition	Greater purity of fractions and better orientation towards appropriate processing	It depends on the infrastructure, the quality of the selection, and the behavior of the users
Reuse	Extending product life	It reduces the generation of waste and preserves the functional value of the product	It depends on the condition, quality, and marketability of the product
Mechanical recycling	Obtaining fibers and secondary materials by physical processing	Simpler and more technologically accessible application	There is shortening and degradation of fibers
Chemical recycling	Recovery of polymers or raw materials from complex textile flows	It enables better material recovery, especially with certain synthetic fibers	Higher costs, more complex processes, and higher entry control requirements

Data from Table 2 indicate that sustainable management of textile waste is not limited to waste treatment, but to the establishment of a technically reliable system that directs textile flows to the most suitable form of reuse or recycling. Identification and sorting technologies play a particularly important role in that chain, because they determine whether waste textiles will be directed towards reuse, mechanical recycling, or chemical recycling. Therefore, in modern practice, automated solutions for the recognition of composition and separation of textiles are increasingly being developed, which is the basis of the next chapter [2, 3].

3. Automated sorting and the role of sensor systems

One of the key technical obstacles to more efficient textile recycling is the reliable identification of the fibrous composition of the waste material. Manual sorting is slow, labor-intensive, and error-prone, especially for products made from mixed fibers, which is why it represents a significant limitation for directing textiles to the appropriate further processing flow [7]. NIR (Near-Infrared) spectroscopy plays an increasingly important role in modern textile classification systems, which enables the identification of materials based on the characteristic reflected spectrum. The advantage of this approach is that it enables quick and non-destructive recognition of material composition, without the need for complex sample preparation [7]. In this way, NIR represents an important engineering tool for increasing the purity of output fractions and more precisely directing waste textiles towards reuse, mechanical, or chemical recycling [5, 7].

An example of an integrated sensor-robot system for automated waste sorting is shown in Picture 1 [9].
The results of recent research confirm that this approach has a high practical value. Du et al. [7] developed an online system for the identification and automatic sorting of 13 types of textile waste using NIR spectroscopy and convolutional neural networks. In that research, the accuracy of identification and sorting was reported to be greater than 95%, while the time to recognize and direct each sample was less than 2 seconds. The system is based on the spectral range from 901 to 2500 nm and is designed as an intelligent, efficient, and non-destructive solution for automatic textile sorting.

In addition to textile-specific research, technical literature shows that in practice, automated sorting is not based on a single sensor, but on a combination of several system components [8]. According to Uremović [8], the ballistic separator is used to separate waste into different fractions, while the NIR separator is used to distinguish between types of materials, with their combined application giving better results than individual use. Also, [8] describes the ZenRobotics system, in which the measuring unit uses 2D and 3D cameras to determine the dimensions and orientation of the waste flow, while the sensing unit combines NIR and VIS sensors, a laser, and a metal detector, and the manipulator then separates the recognized components of the waste.



Picture 1. *Integrated sensor-robotic system for automated waste sorting [9]*

From the point of view of sustainable management of textile waste, the importance of automated sorting is not only in speeding up the process, but above all in increasing the accuracy of identification and purity of separated fractions [7, 9]. The more precise the classification according to the composition of the material, the greater the possibility to direct the textile to an adequate form of further processing, while reducing resource losses and increasing the potential for circular valorization of textiles [7]. The European Commission in the EU Strategy for Sustainable and Circular Textiles emphasizes the need for the development of innovative capacities for fiber-to-fiber recycling and the reduction of burning and landfilling of textiles.

4. Engineering approach: eco-design and circular models

The transition from a linear model of production and consumption to a circular system depends not only on the development of recycling technologies, but also on the way textile products are designed in the design phase. The European Commission in the EU Strategy for Sustainable and Circular Textiles emphasizes that textile products should be more durable, easier to repair, reuse, and recycle, with a reduction in the presence of hazardous substances and a greater use of fiber-to-fiber recycling [5]. This means that eco-design in the context of textiles is not only an aesthetic or market issue, but a concrete engineering prerequisite for more efficient waste management.

The key problem in textile recycling is represented by mixed materials, complex product constructions, and additional components that make it

difficult to identify the composition, separation, and further processing of textiles [3]. That is why eco-design favors solutions such as the use of monomaterials, the reduction of unnecessary fiber mixtures, the standardization of additives, and better information about the composition of products. When the composition and construction of the product are simpler and more clearly defined, the precision of sorting increases, the contamination of recycling streams decreases, and the possibility of obtaining higher quality secondary raw materials increases [3, 7].

In this context, the digital passport of the product takes on special importance as a tool for traceability and access to information about the composition, origin, maintenance, and possibilities of further processing of textiles. The European Parliament, in the study on the digital product passport for the textile sector, indicates that such an approach can improve traceability, transparency, and circularity in the entire textile value chain [10]. At the level of the EU regulatory framework, the digital passport of products is set as a key instrument of the future requirements of sustainable product design, to facilitate informed consumer decisions and more effective enforcement of regulations. From an engineering point of view, this means that successful textile recycling does not start at the sorting plant, but much earlier, i.e., in the phase of designing the product and planning the information that will accompany the product throughout its entire life cycle. Therefore, eco-design and circular models do not represent a supplement to sorting and recycling technologies, but their necessary prerequisite in establishing a sustainable textile waste management system [10].

5. Conclusion

Sustainable management of textile waste represents a complex engineering response to the growing environmental pressures generated by the production, consumption, and disposal of textiles. The analysis in the paper shows that the problem of textile waste does not arise only from its quantities, but also from the loss of raw materials, water, energy, and other resources built into the product during its life cycle. Particular importance should be assigned to automated sorting based on NIR spectroscopy and sensor-robotic systems, since such solutions improve the identification of material composition and the purity of separated fractions. At the same time, the transition to a circular model depends on designing textile products that are more durable,

repairable, and recyclable. Therefore, the combination of technological innovation and product-oriented engineering approaches is a key prerequisite for reducing environmental impacts and improving the circularity of textile flows.

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