NANOCELLULOSE IN TEXTILES: A POTENTIAL RESOURCE FOR SUSTAINABLE TEXTILE MANUFACTURING

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Abstract: *The increasing need for sustainable materials has spurred interest in renewable biomaterials, with nanocellulose emerging as a particularly promising candidate. Sourced from natural cellulose, nanocellulose offers biocompatibility, biodegradability, and a high surface-area-to-volume ratio, making it suitable for a wide range of applications. It can be processed into nanofibers and nanocrystals, allowing the production of suspensions, thin films, and elongated fibers. In the textile sector, adopting environmentally responsible technologies is becoming essential to reduce ecological impact. Cellulose-based textiles, manufactured using processes that minimize water pollution, provide a sustainable alternative to conventional approaches. Advances in nanocellulose-based dyeing methods have also led to substantial reductions in water usage and the need for toxic chemicals, supporting a greener production cycle. Additionally, nanocellulose composites, including nanofibrillated cellulose (NFC) and cellulose nanocrystals (CNC), are increasingly used as fillers in textile composites to improve mechanical strength while remaining recyclable and cost-effective. Overall, these developments position nanocellulose as a key contributor to sustainable innovation, not only in textiles but across multiple industries, with ongoing research further strengthening its role in the transition toward eco-friendly solutions.*

Keywords: Cellulose, Green biomaterials, Nanofibers, Nanocrystals, Water pollution reduction.

NANOCELULOZA U TEKSTILU: POTENCIJALNI RESURS ZA ODRŽIVU PROIZVODNJU TEKSTILA

Apstrakt: *Rastuća potreba za održivim materijalima usmerila je pažnju na biomaterijale iz obnovljivih izvora, pri čemu se nanoceluloza izdvaja kao veoma obećavajuća opcija. Dobijena iz prirodne celuloze, nanoceluloza poseduje biokompatibilnost, biorazgradivost i visok odnos površine i zapremine, što je čini pogodnom za različite primene. Može se preraditi u nanovlakna i nanokristale, omogućavajući stvaranje suspenzija, tankih filmova i izduženih vlakana. U tekstilnoj industriji usvajanje ekološki odgovornih tehnologija postaje ključno za smanjenje negativnih uticaja na životnu sredinu. Tekstili na bazi celuloze, proizvedeni procesima koji smanjuju zagađenje vode, predstavljaju održivu alternativu konvencionalnim metodama. Pored toga, napredak u tehnikama bojenja zasnovanim na nanocelulozi značajno je smanjio potrošnju vode i upotrebu toksičnih hemikalija, doprinoseći zelenijem lancu proizvodnje. Nanocelulozni kompoziti, uključujući nanofibriliranu celulozu (NFC) i nanokristale celuloze (CNC), koriste se kao punila u tekstilnim kompozitima radi poboljšanja mehaničke čvrstoće uz očuvanje reciklabilnosti i isplativosti. Ova dostignuća naglašavaju potencijal nanoceluloze da podstakne održive inovacije ne samo u tekstilu, već i u različitim industrijama. U toku istraživanja nanoceluloza se sve više prepoznaje kao ključni materijal u prelasku ka ekološki prihvatljivim rešenjima.*

Ključne reči: celuloza, zeleni biomaterijali, nanovlakna, nanokristali, smanjenje zagađenja vode.

1. INTRODUCTION

Due to its sustainability and versatility, nanocellulose has emerged as a very prominent material in the textile sector [1]. Water, energy, and raw material are well known hallmarks of the textile industries, and textile waste and water waste are produced in large volumes [2]. Nanocellulose, a derivative of cellulose (the most common natural polymer) and is unique since it is biodegradeable, renewable, and non-toxic. Such advantages make it an interesting alternative to synthetic fibres and additives [3]. Many different applications are possible with its excellent properties, such as a large surface-area-to-volume ratio, high mechanical strength, flexibility, and controllable physical/chemical properties. They involve enhancement of textile composites, fabrication of water resistant, UV resistant and antimicrobial functional coatings [10,11].

The rising problem of textile waste which is being fueled by the rise in production and changing consumption patterns makes better solutions to textile waste a vital necessity [4]. It is possible to extract nanocellulose using numerous waste items such as textile waste, agricultural waste, and paper waste and transform possible pollutants into a resource. This is one of a circular economy [56]. CNFs and cellulose nanocrystals (CNCs) have been well explored. In CNCs, strengths and stiffness are high due to their rod-like and crystalline structure, whereas CNFs consist of a tangled network and can increase mechanical properties and are used to produce functional coating in textile products [8 10]. More advanced methods, such as enzyme-assisted extraction, chemical, and acid hydrolysis, and addition of nanomaterials, Dunaliella-ZnO nanoparticles are valuable to make smart textiles of recycled polyester and cotton. The given textiles have multidimensional qualities and low environmental footprint [5,15,16].

Although it is likely, much commercial application of nanocellulose in the textiles industry is still marred by a few obstacles including prohibitive costs of production, energy-intensive synthesis, and the difficulty of getting the fibers to separate homogenously in textile material [12]. To address these difficulties, continuous studies in more environmentally friendly production processes, such as the use of sustainable solvents, enzyme treatment, and novel processing technologies are being conducted to avoid the trade-offs of performance or production scale [5]. Also, techno-economic studies and life cycle assessments are playing a growing role ensuring that nanocellulose based textiles can be sustainable not just environmentally but also economically in the textile industry [14].

This review hopes to provide an insightful overview of nanocellulose fiber production, modification and application in sustainable textile production. This will examine the ways nanocellulose may be used in place of conventional materials, to upgrade the qualities of fabrics, and to supplement one- and zero-waste economy paradigms. Through this review, based on its current advancements and ongoing issues and the prospects, it has been possible to re-emphasize that nanocellulose has the potential to be a major player in the creation of high performance and environmentally sustainable textiles which are in line with global goals of sustainability.

2. DIFFERENT METHODS OF NANOCELLULOSE FIBER PRODUCTION

2.1. Acid hydrolysis

Nanocellulose fibers can be produced through acid hydrolysis, most commonly using sulfuric acid (H_2SO_4) or hydrochloric acid (HCl). The choice of acid determines whether cellulose nanocrystals (CNCs) or cellulose nanofibrils (CNFs) are obtained. Sulfuric acid treatment typically yields CNCs with high aspect ratios and excellent water dispersibility [17,18], while hydrochloric acid hydrolysis is effective for preparing aqueous CNF suspensions, though pH adjustment and surfactants are often required for stability [19]. Combining mechanical pretreatment with acid hydrolysis under optimized enzymatic conditions has further improved yield and tunability [20]. Similarly, integrating acid hydrolysis with sonication has proven effective for producing nanocellulose from biomass sources such as enset fiber [21].

2.2. Alkaline hydrolysis and enzymatic hydrolysis

Alkaline treatment, when paired with enzymatic hydrolysis, is another promising route for nanocellulose production. Enzymatic hydrolysis uses cellulase enzymes to selectively break down cellulose fibers into nanofibrils, offering both scientific and commercial advantages [16,23,24]. Although less studied than acid- or alkali-based methods, the enzymatic approach has unique benefits, including milder processing conditions and reduced environmental impact. Studies show that combining NaOH treatment with enzymatic hydrolysis improves nanocellulose yield [22], while pairing enzymatic hydrolysis with homogenization produces nanocellulose of higher aspect ratio and with fewer defects compared to acid hydrolysis [24]. Together, alkaline and enzymatic methods provide a practical, eco-friendly pathway for sustainable nanocellulose production.

2.3. Mechanical treatment

Mechanical methods are also widely studied for nanocellulose production. Lee et al. investigated non-woody fibers, such as paper mulberry bast fiber (PMBF) and cotton linter mixed pulp (CLMP), as raw materials for nanocellulose preparation [18]. Redlinger-Pohn and Lim analyzed homogenization flow events to better understand the fibrillation of plant fibers [25]. Similarly, Fahma et al. reviewed techniques for producing transparent nanopaper and highlighted its applications in optoelectronics [2]. Other works have explored oil palm empty fruit bunches as a feedstock for nanocellulose, focusing on how varying nanocellulose content influences material properties [26]. Collectively, these studies underscore the feasibility of mechanical treatment methods for producing nanocellulose from diverse plant-based sources.

2.4. Template-assisted synthesis

Template-assisted synthesis has gained attention as a method to design advanced nanocellulose-based materials. Cellulose nanofibers (CNFs) offer desirable features—mechanical strength, porosity, high water retention, surface reactivity, and a fibrous network—that serve as a scaffold for templating novel materials [27,28]. This approach has been applied across fields such as catalysis, energy storage (batteries, supercapacitors, electrodes), construction, biomaterials, and membrane technologies [29]. While carbon nanofibers show potential as reinforcements in polymers, nanoscale incorporation poses challenges [30]. Recent advances, such as Pickering emulsion templating, have enabled the fabrication of CNF–polymer composite films and core–shell microparticles [31]. Overall, template-assisted strategies allow tailoring of nanocellulose properties for specialized applications.

3. PROPERTIES OF NANOCELLULOSE FIBERS

Nanocellulose fibers possess a wide array of functional properties that support their growing use in advanced materials. Their tensile modulus ranges between 13–23.9 GPa for long fibers [32], while crystalline nanocellulose shows densities of 1.5–1.6 g/cm^3 and a much higher Young's modulus compared to glass fibers, reaching ~70 GPa [33]. Mechanical performance is coupled with strong elongation behavior; for example, PVA composites reinforced with nanocellulose exhibit increased tensile strength and elongation with higher fiber loading [34]. Sugarcane bagasse-derived nanocellulose films demonstrated tensile strengths of 3.177–3.315 MPa and elongations of 3.7–10.9% [35].

Aspect ratio, a critical factor in reinforcement performance, varies depending on the cellulose source. Tunicate-derived CNCs achieve higher aspect ratios (70–100) than those from terrestrial sources [36,37]. Crystallinity also plays a vital role, influencing not only mechanical performance but also biological interactions, such as immunological responses in vitro and in vivo [38–40]. Surface chemistry governs nanocellulose stability and reactivity, as reflected in zeta potential measurements [36] and evaluations of biocompatibility [39]. Tensile strength of nanocellulose long fibers typically falls between 224–383 MPa [32]. Beyond mechanics, nanocellulose exhibits functional properties: batch studies have shown its ability to remove heavy metals such as Cd(II), Pb(II), and Ni(II) at capacities of 9.7, 9.4, and 8.6 mg/g, respectively [41]. More recently, hybrid nanocellulose fibers coated with esterified poly(vinyl alcohol), citric acid, and lignin have demonstrated high strength, multifunctionality, and durability [42].

4. NANOCELLULOSE FIBER APPLICATIONS IN SUSTAINABLE TEXTILES

4.1 Nanocellulose fibers as reinforcing agents in textile composites

Nanocellulose fibers have gained significant attention as reinforcing agents in textile composites due to their exceptional mechanical, thermal, and barrier properties, as well as their renewable and biodegradable nature. In cotton-based composites, Liang et al. demonstrated that fibrillating cotton fibers into nanofibers during compounding substantially enhanced tensile and flexural strength, along with the moduli, of polypropylene composites [43]. Similarly, Sapuan et al. reported that starch biopolymer composites reinforced with nanocellulose fibers exhibited marked improvements in both mechanical and thermal performance [3]. The potential of nanocellulose in hybrid fiber systems and in combination with other nanomaterials has also been highlighted, offering promising avenues for industrial-scale applications [44]. Beyond traditional reinforcement, nanocellulose composites have been explored in Pickering emulsions, integration with metal nanoparticles, and biomedical applications, demonstrating their versatility across multiple domains [45,46].

In polyester and nylon composites, nanocellulose fibers continue to enhance performance characteristics.

Polyester composites reinforced with nanocellulose exhibit superior mechanical, barrier, and thermal properties, while nylon composites incorporating modified nanocellulose-such as caprolactone-modified (CNF-CL) and polyisocyanate-modified (CNF-JQ) fibers—show significant improvements in tensile and flexural strength, as well as moduli [44,47]. The incorporation of hybrid fibers and organic additives has enabled the production of value-added materials on a larger scale. Furthermore, starch biopolymer composites and polypropylene nanocomposites derived from textile waste offer sustainable and mechanically robust alternatives to conventional synthetic fibers, underscoring the role of nanocellulose in advancing eco-friendly textile solutions [3,43,44]. Overall, nanocellulose fibers provide a versatile, sustainable, and high-performance reinforcement strategy for a wide array of textile composites, bridging the gap between enhanced functionality and environmental responsibility.

4.2 Nanocellulose Fibers for Functional Textile Coatings

Nanocellulose fibers have demonstrated remarkable versatility in the development of functional textile coatings, offering environmentally friendly solutions with enhanced performance. In water-resistant applications, they form effective barriers against water, gases such as CO_2 and O_2, volatile compounds, and grease, making them suitable for textiles and food packaging, while research continues on dual-function coatings that retain stability under varying humidity conditions [48–50]. Antimicrobial nanocellulose coatings inhibit the growth of bacteria, mold, mildew, and algae, and the inclusion of additives such as silver ions improves durability and efficacy, making these coatings suitable for medical devices, healthcare environments, and humid settings, while preventing microbial proliferation and extending the lifespan of coated textiles [52–56]. Nanocellulose fibers also enhance flame-retardant properties in thermal insulating materials, employing strategies such as bio-based fire retardants (sulfonated kraft lignin and nanoclays) combined with microfibrillated cellulose to distribute and adhere fire-retardant particles, nanocrystalline cellulose produced via silylation for thermal insulation and sustainability, sodium bicarbonate-incorporated CNF aerogels for improved fire resistance with structural rigidity, and Layer-by-Layer functionalized cellulose fibers creating low-density, porous networks with superior flame-retardant performance, as illustrated in Figure 1, while nanofillers in cotton fabrics further boost flame resistance [57–62]. In UV-resistant coatings, nanofibrillated cellulose, cellulose nanocrystals, and cellulose nanowhiskers act as reinforcing fillers, providing protection against harmful ultraviolet radiation, enhancing durability, and enabling sustainable fabrics with high mechanical strength, biocompatibility, and tunable surface chemistry, as illustrated in Figure 2 [28,63–67]. Self-cleaning coatings utilize photocatalytic reactions on fabric surfaces with catalysts such as titanium dioxide and zinc oxide, where higher TiO_2 loading increases efficiency, and additional components including oil palm boiler ash, chitosan, and cellulose nanofibers further enhance performance; these coatings can impart antibacterial activity, UV protection, and sustained scent release, while zinc oxide nanoparticles promote photocatalytic degradation in cotton textiles [68–72]. These applications collectively illustrate how nanocellulose fibers provide multifunctional, sustainable, and high-performance coatings for modern textile applications.

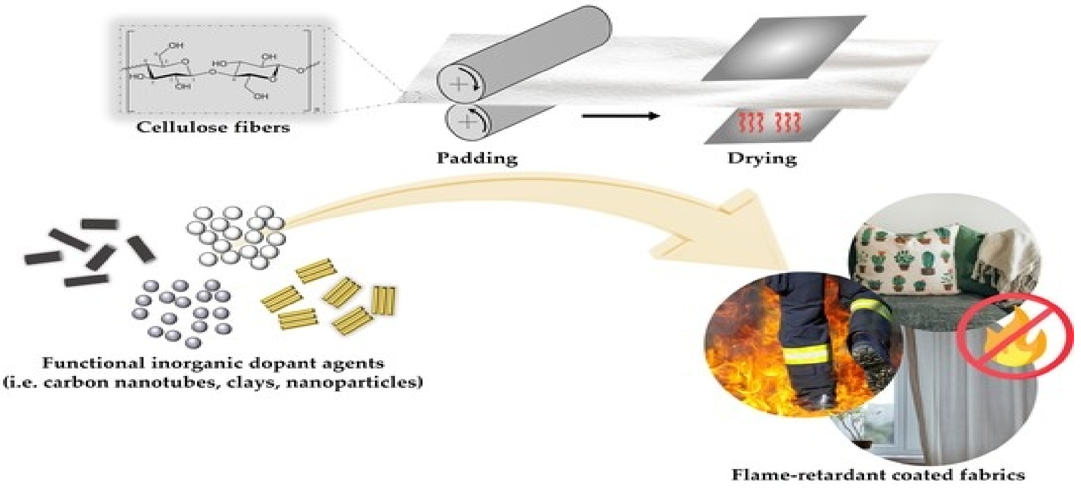

Figure 1: Nanofillers in cotton fabrics enhance their flame-retardant performance [62].

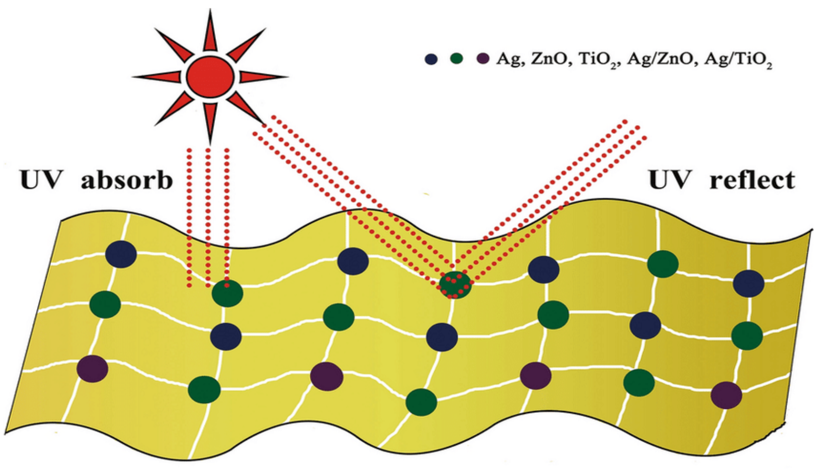

Figure 2: The schematic mechanism of UV protective coating involves the absorption [67].

5. NANOCELLULOSE FIBERS FOR THE DEVELOPMENT OF NEW SUSTAINABLE TEXTILE MATERIALS

Nanocellulose fibers are increasingly employed to develop a variety of sustainable textile materials, demonstrating remarkable versatility across aerogels, hydrogels, films, and nonwovens. Nanocellulose-based aerogels are lightweight materials with highly porous three-dimensional structures and large surface areas, produced via supercritical drying, and offer advantages such as biodegradability, sustainability, and regenerative potential, often sourced from waste cotton, textile fibers, or cellulose [73–76]. These aerogels have shown great promise as reusable and recyclable oil absorbents, capable of floating and safe incineration along with absorbed oil, and aerogels from textile waste fibers display excellent oil and solvent adsorption and favorable thermal properties [74,75]. Porous coaxial fibers derived from nanocellulose aerogels provide thermal insulation, marking significant progress in eco-friendly insulating materials, and aerogels have been successfully incorporated into thermoregulating fabrics without compromising breathability [76,77]. Nanocellulose-based hydrogels, particularly those derived from nanofibrillated cellulose (NFC), serve as efficient carriers for textile dyes, minimizing environmental contamination from conventional dyeing processes, while also finding applications in paper and textile coatings and film composites due to their low thermal expansion and eco-friendly nature [78–82]. Nanocellulose films, including cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs), are abundant, cost-effective, biodegradable, and easily produced, providing sustainable alternatives to plastic coatings in textiles, improving mechanical strength, and allowing customization for hydrophobicity, antimicrobial activity, and UV resistance, with additional applications in stabilizing historical papers and fabrics due to their strength, transparency, and lightweight characteristics [83–85]. Furthermore, nanocellulose-based nonwovens leverage CNFs and CNCs to replicate the properties of natural fibers like cotton, offering high aspect ratios, excellent wicking capabilities, and tunable surface characteristics; bioinspired designs enable multifunctional materials that are biodegradable and mechanically robust, positioning nanocellulose nonwovens as a sustainable alternative capable of transforming the textile industry toward greener production [86,87].

6. CHALLENGES AND FUTURE PROSPECTS OF NANOCELLULOSE FIBER IN SUSTAINABLE TEXTILES

6.1 Challenges in the Commercialization of Nanocellulose Fiber for Textile Applications

Despite the growing recognition of nanocellulose fibres in the textile industry due to their favorable physical and chemical properties, abundance, and sustainability [88], their commercialization faces several significant challenges. One major obstacle is the high cost of production, which varies according to the manufacturing technique and the cellulose source; for instance, cellulose nanofibers (CNFs) produced via sulfuric acid hydrolysis cost approximately USD 3.19/kg, making them about 70.9 times cheaper than CNFs obtained through TEMPO oxidation [89], yet still substantially more expensive than conventional fibres like cotton and polyester. In addition to cost, scalability remains a concern, as industrial-scale production of nanocellulose, although reaching several tonnes per day, is still limited compared to traditional textile fibres [90]. Another critical issue is dispersibility, since the high surface area and strong hydrogen bonding of nanocellulose fibres often lead to aggregation, making it challenging to achieve uniform dispersion in aqueous or other solvent systems. Techniques such as mechanical fibrillation, chemical modification, and surface functionalization have been explored to address this limitation [91].

Furthermore, durability within textile matrices poses a significant hurdle because nanocellulose fibres are susceptible to degradation when exposed to moisture, heat, and ultraviolet light [41]. Enhancing the longevity of these fibres in textile composites is therefore crucial, and strategies such as crosslinking, coating, or blending with other fibres have been employed to improve stability [88]. Overcoming these interconnected challenges requires a multifaceted approach that focuses on developing scalable and cost-effective production methods, improving dispersibility and durability, and exploring innovative applications and markets for nanocellulose fibres within the textile sector.

6.2 Future Prospects for New and Innovative Nanocellulose Fiber-Based Textiles

The future of nanocellulose fiber-based textiles is poised to focus on refining production methods, developing advanced composites, creating functional coatings, and engineering new sustainable textile materials. Advancements in production are expected from emerging technologies such as top-down approaches, which break down cellulose fibers from lignocellulosic biomass into nano-sized particles, improving efficiency, scalability, and uniformity [92]. Functionalization of nanocellulose will continue to play a critical role, enhancing interfacial bonding, mechanical strength, and overall performance in polymer composites, enabling broader applications in textiles, biomedical devices, and other functional materials [15]. Exploration of novel cellulose sources and innovative synthesis techniques is projected to provide more sustainable and cost-effective alternatives, while techno-economic assessments will ensure that emerging methods remain both feasible and scalable for industrial adoption [93]. The expansion of nanocellulose-based biomaterials with multifunctional features, such as improved thermal stability, biocompatibility, and tunable surface properties, is expected to drive research and commercialization, with advanced processing methods like solution casting, melt processing, and extrusion facilitating the production of high-performance nanocomposites [7,90]. Continuous modification and tailoring of nanocellulose fibers will enhance properties including hydrophobicity, antimicrobial activity, UV resistance, and flame retardancy, broadening the functional potential of these textiles. In parallel, the development of nanocellulose fiber-based composites addresses inherent limitations such as high hydrophilicity and gel-like structures due to abundant hydroxyl groups [65]. Modification strategies are enhancing mechanical performance, degradability, and applicability in natural fiber composites, while nanocellulose-reinforced polymer composites are achieving higher tensile strength and durability [94]. Advanced applications, including flexible energy storage devices and starch biopolymer composites, highlight the sustainability, unique architectures, and superior functional properties of nanocellulose-based materials [3,95]. Functional coatings represent another promising area, with innovations in surface chemistry improving adhesion, durability, and eco-friendliness for both natural and synthetic fibers, enabling high-quality sustainable coatings for textiles and paper [41,65,80,96]. Finally, the development of new nanocellulose-based textile materials demonstrates the potential to meet global environmental challenges while delivering superior performance. Spinning nanocellulose into filaments produces fibers with mechanical properties comparable to high-performance synthetics [84], while modifications to nanocellulose-derived carbon fibers enhance porosity, surface area, and functionality [97]. Green composites incorporating nanocellulose are gaining attention due to their lightweight, cost-effective, and mechanically robust nature, suitable for biomedical, engineering, and other high-value applications [7]. Integration of nanocellulose optical waveguides into yarns further illustrates the potential for sustainable smart textiles with optical sensing and other advanced functionalities [98]. These ongoing innovations underscore the role of nanocellulose fibers as a foundation for sustainable, high-performance, and environmentally conscious textiles capable of meeting future industrial and ecological demands.

7. CONCLUSION

Nanocellulose fibers have emerged as a highly promising material for the advancement of sustainable textiles due to their unique physicochemical properties, including high mechanical strength, biodegradability, low density, and tunable surface chemistry. Their applications span a wide range, from reinforcing textile composites such as cotton, polyester, and nylon, to enabling functional coatings that impart water resistance, antimicrobial activity, flame retardancy, UV protection, and self-cleaning capabilities. Beyond conventional textile enhancements, nanocellulose-based materials, including aerogels, hydrogels, films, and nonwovens, offer innovative solutions for environmentally friendly and high-performance textile products, addressing both functional and ecological demands.

Despite these advantages, several challenges remain for the widespread commercialization of nanocellulose fibers, including high production costs, limited scalability, dispersibility issues, and durability concerns within textile matrices. Addressing these limitations through cost-effective manufacturing, improved functionalization, and innovative composite and coating development is critical for translating laboratory successes into industrial applications.

Looking ahead, the future prospects of nanocellulose fibers in sustainable textiles are highly encouraging. Ongoing research in advanced manufacturing techniques, novel composite materials, functional coatings, and next-generation textile architectures is poised to unlock the full potential of nanocellulose. By integrating these materials into the textile industry, it is possible to create eco-friendly, high-performance textiles that meet modern sustainability standards, reduce environmental impact, and offer versatile functional properties. In conclusion, nanocellulose fibers represent a transformative avenue in the pursuit of sustainable, high-quality, and innovative textile solutions.

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