Nanocellulose in Textiles: A Potential Resource for Sustainable Textile Manufacturing

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Abstract

In recent times, there has been a discernible focus on the development of environmentally friendly and sustainable biomaterials obtained from renewable sources. Scientists are now investigating the prospective applications of nanocellulose, a biocompatible substance derived from natural cellulose. The aforementioned substance exhibits notable characteristics, such as a substantial surface area to volume ratio, with its compatibility with biological systems and capacity to undergo degradation. Nanocellulose has the capability to undergo transformation into nanofibers and nanocrystals, so enabling the generation of diverse structures, including elongated nanofibers, suspensions, and films. In the textile industry, there is a growing need to adopt sustainable techniques in order to address and minimize the negative environmental impacts. The current focus is on the advancement of environmentally sustainable alternatives in the realm of textile production, namely cellulose-based materials. These textiles are being created using processes that aim to minimize water pollution. In addition, recent advancements in dyeing methods have used nanocellulose to effectively reduce water consumption and eliminate the need for toxic materials. Nanocellulose nanocomposites, such as nanofibrillated celluloses (NFCs) and cellulose nanocrystals (CNCs), are increasingly used as fillers in textile nanocomposites to enhance their mechanical characteristics due to their cost-effectiveness and recyclability. The advancements achieved in the field of nanocellulose-based materials and technology exhibit considerable promise in the development of ecologically friendly solutions across several industries.

Keywords: *Cellulose-based textiles, Green biomaterials, Nanofibers, Nanocrystals, Water pollution reduction*

1. Introduction

Nanocellulose fibre is a substance obtained from cellulose, a naturally occurring polymer present in diverse sources, including plants and agricultural byproducts. Nanoparticles having distinctive physical, chemical, and morphological attributes are generated from cellulose fibres by mechanical or chemical processing. The nanocellulose fibre exhibits notable characteristics such as a substantial surface-to-volume ratio, elevated tensile strength, stiffness, and flexibility, along with commendable dynamic mechanical, electrical, and thermal capabilities. The use of this technology spans across several domains, including transparent nanopaper devices, electrical and optoelectronic devices, medicine, cosmetics, and health care. Recent research has examined the investigation of nanocellulose fibre synthesis from several sources, including Styphnolobium japonicum, Cryptomeria fortunei, Pinus yunnanensis, starch, and coconut fibre[1-5]. For sustainable textiles, nanocellulose fibres also provide a number of benefits. First and foremost, the use of renewable and biodegradable materials renders them ecologically sustainable and contributes to waste reduction. Additionally, it should be noted that nanocellulose fibres possess exceptional strength and modulus properties, hence imparting a notable level of resilience and endurance to textile goods. Moreover, these materials have a low density, leading to the production of lightweight fabrics that provide enhanced comfort when worn. Along with that, nanocellulose fibres have favourable barrier characteristics, including efficient gas barrier performance, hence offering potential advantages for implementation in many sectors such as packaging and other industrial applications. Ultimately, nanocellulose fibres exhibit functional diversity, enabling the integration of many qualities and functions into textiles, such as antibacterial attributes or improved mechanical capabilities[6-8]. The use of nanocellulose fibres has promise for the production of sustainable textiles; yet, some unresolved challenges need attention. The issue of production costs poses a significant challenge to the profitability of large-scale industrial operations[9]. The issue of scalability arises when considering the necessity of increasing the production of nanocellulose fibers in order to satisfy the requirements of the textile industry[10]. The equal distribution of fibers inside textile matrices is a crucial factor in achieving optimum performance[11]. Therefore, dispersability plays a significant role in this regard. Durability emerges as a pivotal factor to be taken into account, given that the fibers must possess the capacity to endure the demands of regular use while maintaining their functional integrity[12]. Addressing these challenges will be crucial for the successful integration of nanocellulose fibers into sustainable textile applications. It is possible to meet the growing demand for environmentally friendly textiles and attract funding from the government for research and development through innovative manufacturing techniques using nanocellulose fibres[9]. Other than that nanocellulose originates from sources of biomass and is a material that has non-toxic, biocompatible, and ecologically sustainable properties. It has the potential to be used in the production of biobased fibres that show exceptional performance characteristics[13]. Each of these fibres has the ability to compete with synthetic fibres, such as glass fibres and carbon fibres, while offering distinct functionality[14]. And the surface implementation of nanocellulose enables its effective application as an outstanding material in the reinforcing of polymers[15]. The application of nanocellulose to textile manufacturing is in accordance with the growing awareness and focus on environmental and sustainability concerns, as well as the use of renewable nature's resources[16]. Additionally, producing nanocellulose by enzymatic hydrolysis using cellulases is a sustainable method that makes use of leftover pulp and paper industry materials. The progress achieved through the manufacture of nanocellulose and its potential use in sustainable textiles makes it an appealing field for scientific research and invention, with the possibility of receiving governmental backing.

2. Nanocellulose Fiber Production

2.I Different methods of nanocellulose fiber production

2.I.A Acid hydrolysis

Nanocellulose fibres may be manufactured through the use of acid hydrolysis methodology. Multiple acids, notably sulfuric acid (H2SO4) and hydrochloric acid (HCl), have been exploited for this purpose. The outcome of cellulose hydrolysis, whether it results in cellulose nanocrystals (CNCs) or cellulose nanofibrils (CNFs), depends on the particular type of acid employed Cellulose nanocrystals (CNCs), known for their high aspect ratios and superior dispersibility in solutions of water, are often created through the utilisation of sulfuric acid[17, 18]. However, it is possible to use hydrochloric acid hydrolysis as a way to get sound aqueous suspensions of CNFs. The procedure still needs pH optimisation and the inclusion of surfactants for better stability[19]. The use of mechanical pretreatment methods in combination with acid hydrolysis conducted under precise enzymatic conditions has shown significant outcomes in the generation of nanocellulose, characterised by an impressive output and customizable qualities[20]. Likewise, the simultaneous use of acid hydrolysis and sonication has shown efficacy in the production of nanocellulose from sustainable biomass sources such as enset fibre[21].

2.I.B Alkaline hydrolysis & Enzymatic hydrolysis

Alkaline hydrolysis and enzymatic hydrolysis are two techniques used in the manufacturing process of nanocellulose fibres. The combination of alkaline treatment and enzymatic hydrolysis has been investigated as an approach to improving the synthesis of cellulose nanofibrils[22]. Enzymatic hydrolysis is a promising novel method for the manufacture of nanocellulose fibrils, presenting benefits from both scientific and commercial perspectives[16, 23]. This technique converts cellulose fibres into nanocellulose by using enzymes that break down cellulose[24]. The literature has relatively little exploration of the enzymatic approach for nanocellulose production compared to nonenzymatic approaches such as alkaline or acidic procedures. However, the enzymatic pathway has distinctive properties that might potentially provide benefits[16, 23]. The efficacy of cellulose nanofibril synthesis has been shown by the use of a combination of NaOH and enzymatic hydrolysis[22]. The combination of enzymatic hydrolysis and cellulose fibre homogenization has been shown to provide nanocellulose with a higher aspect ratio and less aggressive characteristics compared to acidic treatment[24]. Both alkaline hydrolysis and enzymatic hydrolysis are essential processes in the production of nanocellulose fibres, and their integration exhibits promise for the effective and environmentally friendly manufacture of nanocellulose.

2.I.C Mechanical treatment

The creation of nanocellulose fibres by mechanical treatment has been investigated in several academic works. The researchers, Lee et al., conducted a study to assess the appropriateness of non-woody fibres, namely paper mulberry bast fibre (PMBF) and cotton linter mixed pulp (CLMP), in the manufacturing process of nanocellulose[18]. Redlinger-Pohn and Lim conducted a study with the purpose of observing and quantifying events related to the flow of homogenization. This aspect of research is significant in understanding the fibrillation process of plant raw materials[25]. In a review article authored by Fahma et al., a summary was provided of the existing techniques used for the production of transparent paper using cellulose fibres. The study also discussed the many uses of transparent nanopaper devices[2]. Furthermore, the use of oil palm empty fruit bunches as a raw material has facilitated the production of nanocellulose fibres. The investigation of the impact of nanocellulose content on the qualities of these fibres has also been conducted[26]. A considerable number of studies emphasise the possibility of using mechanical methods of treatment in the production procedure of nanocellulose fibres acquired from diverse sources.

2.I.D Template-assisted synthesis

In recent years, there has been a growing interest in using cellulose nanofibers (CNFs) as a viable source for templating sophisticated materials, which has shown noteworthy promise[27]. Cellulose nanofibers (CNFs) exhibit distinct features, including mechanical strength, porosity, high water retention, high surface functionality, and an entangled fibrous network. These traits play a crucial role in determining the attributes of the resulting templated materials[28]. The use of templating with CNFs has been extensively investigated across a range of applications, including catalysis, batteries, supercapacitors, electrodes, building materials, biomaterials, and membranes[29]. Plus, carbon nanofibers (CNFs) have the potential to serve as a strengthening agent in polymer composites. yet the process of incorporating CNFs into polymers at the nanoscale presents some difficulties[30]. The use of template-assisted synthesis methods, such as Pickering emulsion templating, has been employed in the fabrication of composite films and core-shell microparticles consisting of cellulose nanofibrils (CNF) and polymers[31]. Primarily, these approaches provide a means to integrate cellulose nanofibrils (CNFs) with polymers on a nanoscale, allowing the fabrication of nanocellulose fibres with customised characteristics.

2.II Properties of nanocellulose fibers

Nanocellulose fibres has a wide range of applications. The following are many fundamental characteristics pertaining to them:

Modulus: The tensile modulus of cellulose long fibres, which are produced from cellulose nanofibers, exhibits a range of values between 13 GPa and 23.9 GPa[32]. The Young's modulus of nanocellulose, which has a density of around 1.5–1.6 g/cm3 for crystalline cellulose, exhibits much greater magnitude compared to glass fibres, estimated to be around 70[33].

Elongation: The elongation at the point of fracture of composites made from cellulose/nanocellulose-reinforced polyvinyl alcohol (PVA) exhibits an upward trend when the loading of cellulose/nanocellulose fibres is increased[34]. The tensile strength and elongation properties of nanocellulose film derived from sugarcane bagasse were reported as 3.177 MPa and 10.93%, respectively. Additionally, the film exhibited a tensile strength of 3.315 MPa and an elongation of 3.7%[35].

Aspect ratio: The aspect ratio, denoted as the ratio of length to diameter (L/d), is a significant characteristic of cellulose nanocrystals (CNC). This parameter plays a crucial role in determining the performance of CNC-reinforced polymers, functional materials, and suspensions[36]. The aspect ratio of CNC derived from tunicates has been shown to exhibit greater values (ranging from 70 to 100) compared to CNC obtained from other sources[37].

Crystallinity: The degree of crystallinity in cellulose nanofibers (CNFs) is a changeable structural characteristic that influences their material performance[38]. The pro-inflammatory and immunological adjuvant effects of cellulose nanomaterials are influenced by their crystallinity and aspect ratio, as seen in both in vitro and in vivo studies[39]. The mechanical characteristics of twisted cellulose nanofibers are affected by the local crystallinity[40].

Surface chemistry: Surface chemistry plays a crucial role in assessing the stability of solutions containing cellulose nanocrystals (CNCs), as shown by the use of zeta potential measurements[36]. The surface reactivity of high-aspect-ratio nanomaterials that are deemed safe for biological applications has been investigated[39].

Tensile strength: The tensile strength of cellulose long fibres produced from cellulose nanofibers varies between 224 MPa and 383 MPa[32]. The batch studies conducted to synthesise nanocellulose fibres demonstrated their capacity to eliminate Cd (II), Pb (II), and Ni (II) with efficiencies of 9.7 mg/g, 9.4 mg/g, and 8.6 mg/g, respectively[41]. The researchers have successfully generated nanocellulose hybrid fibres that possess high strength, multifunctionality, and durability. These fibres are coated with a resin composed of esterified poly (vinyl alcohol), citric acid, and lignin[42].

3. Nanocellulose Fiber Applications in Sustainable Textiles

3.I Nanocellulose fibers as reinforcing agents in textile composites

3.I.A Nanocellulose fiber-reinforced cotton composites

The use of nanocellulose fibres as reinforcing agents in textile composites, such as cotton composites, has been the subject of much research. Liang et al. conducted an experiment where they successfully fibrillated cotton fibres into nanofibers during the compounding process. This resulted in a notable improvement in the tensile and flexural strength, as well as the moduli, of polypropylene composites[43]. In their study, Sapuan et al. examined the progress made in the fabrication of starch biopolymer composites reinforced with nanocellulose fibres. The authors specifically focused on elucidating the mechanical and thermal characteristics of these starch fibres when reinforced with nanocellulose, as highlighted in their work[3]. In their study, Seydibeyoğlu et al. conducted a comprehensive analysis of the utilisation of nanocellulose in composite materials. This research included several aspects, such as hybrid fibre reinforcement and the incorporation of nanocellulose with other nanomaterials. The authors also highlighted the emergence of new opportunities for industrial-scale applications in this field[44]. Jayeoye examined the prospective uses of nanocellulose materials and composites, including their utilisation in stable Pickering emulsions, composites integrated with metal nanoparticles, and in the field of biomedicine[45]. During the research they carried out, Tahir et al. (year) presented a comprehensive examination of nanocellulose, including its extraction techniques, chemical modifications, and diverse uses across several domains such as electronics, paper manufacturing, packaging, and filtering[46].

3.I.B Nanocellulose fiber-reinforced polyester composites

Extensive research has been conducted on the use of nanocellulose fibres as reinforcement elements in textile composites, specifically in the context of nanocellulose fiber-reinforced polyester composites. These composite materials exhibit enhanced mechanical, barrier, and thermal characteristics, rendering them well-suited for a wide range of applications. Researchers have looked into the synthesis of hybrid fibres, sustainable materials, and nanocellulose with other nanomaterials in order to improve the overall performance of these composites[44]. Nanocellulose materials, namely cellulose nanofibers and cellulose nanocrystals, have garnered considerable attention owing to their inherent physicochemical characteristics, which include a high aspect ratio, mechanical durability, biocompatibility, and lack of toxicity. The aforementioned materials have been used in the creation of stable Pickering emulsions as well as in the development of composites containing metal nanoparticles. Additionally, they have found application in many biological contexts, including wound healing and the fabrication of medical implants[45]. Furthermore, researchers have successfully created nanocellulose fiber-reinforced starch biopolymer composites as an environmentally friendly substitute for non-biodegradable plastic composites. These composites exhibit enhanced mechanical and thermal characteristics, as reported in reference[3].

3.I.C Nanocellulose fiber-reinforced nylon composites

The utilisation of nanocellulose, which is fibre, as support agents in clothing and textile composites, such as nylon composites, has been the focus of a great deal of research. Findings from studies reveal that the insertion of nanocellulose fibres, specifically caprolactone-modified nanocellulose (CNF-CL) and polyisocyanate-modified nanocellulose (CNF-JQ), has been viewed as strengthening the mechanical attributes of nylon matrices. The modifications are evident in terms of enhanced tensile and flexural strength, as well as increased moduli[44]. The investigation of incorporating nanocellulose fibres with hybrid fibres and organic substances has been carried out, resulting in the production of value-added products on an enormous scale[47]. Besides, the improved properties of starch biopolymer composites by adding nanocellulose fibres have shown enhancements in mechanical and temperature properties[3]. As well, the use of textile waste for the production of polypropylene nanocomposites revealed a successful translation of cotton fibres into nanoscale dimensions, contributing to improved mechanical characteristics of the composites[43].

3.II Nanocellulose fibers for functional textile coatings

3.II.A Water-resistant coatings

Plenty of study has been done about the use of nanocellulose fibres in the development of water-resistant coatings. Several examples include:

This coating has the capacity to generate a protective barrier that produces resilience towards many compounds, which include water droplets, gases such as carbon dioxide and oxygen, volatile components, and grease. This feature enables nanocellulose coatings suitable for use in food packaging[48].

Cellulose nanofibers have been used in the preparation of hydrophobic coatings on textile substrates[49].

Nanocellulose has tremendous potential as an effective replacement for established fossil-derived and synthetic polymers in the field of cellulosic surface coverings[48].

Future difficulties for nanocellulose-based coatings include the development of dual-function coatings that are water-repellent[48].

Recently published research has provided additional confirmation and expansion of what is already known about the hydrophobic qualities of films and coatings made from nanocellulose. All of these inquiries have shed light on the susceptibility of such materials to the impact of humidity or moisture(figure 1. a)[50].

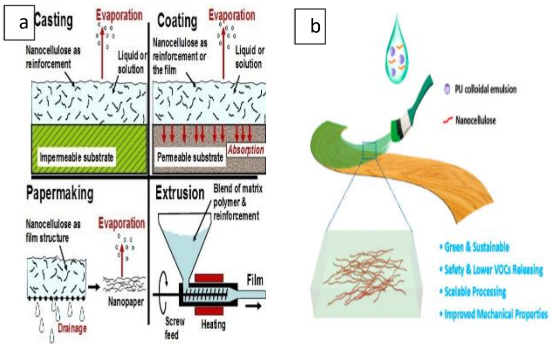

Figure 1. a) Schematic illustrating the four popular ways to make nanocellulose-containing films that are thin, presenting variations in liquid withdrawal[50]. *b) nanocellulose-reinforced water-related polyurethane wood coating schematics*[51]

3.II.B Anti-microbial coatings

Antimicrobial coatings refer to coatings that have been specifically treated with antimicrobial chemicals in order to inhibit the proliferation of bacteria, mould, mildew, or algae on various surfaces. These coatings find use in many sectors, such as healthcare facilities, public venues, residential structures, and medicinal devices. The provided surface protection has been shown to effectively regulate the proliferation of undesired bacteria, resulting in many advantages, including enhanced longevity, improved aesthetics, and safeguarding against pathogenic microorganisms that might cause diseases[52-54]. These coatings use chemical substances to impede the proliferation of infections by inducing perturbations in the cellular membrane. These substances have the ability to impede the proliferation of a wide range of bacteria, mould, and mildew, hence safeguarding surfaces against deterioration and the development of bacterial odours. Additives, such as silver ions, are often used to impede the proliferation of microorganisms. This incorporation of additives enhances the durability and efficacy of these coatings, enabling them to withstand repeated exposure to water and cleaning procedures[52, 55]. Antimicrobial coatings find extensive use throughout several domains, including ornamental paints, protective coatings, medicinal items, gadgets, and surfaces inside medical facilities. Air purifiers provide many advantages in terms of preserving indoor air quality, preventing the proliferation of mould, and ensuring sustained defence against pathogenic microorganisms. The use of these coatings proves to be very advantageous in situations that require strict hygiene standards and in areas with high levels of moisture or humidity. These coatings exhibit the ability to effectively inhibit the development of bacteria and fungi, hence extending the lifespan of items that have been coated[52-56]. This is the reason why it is being used for the purpose of inhibiting the transmission of infections in medical items, equipment, and surfaces[53, 56].

3.II.C Flame-retardant coatings

The use of nanocellulose fibres in the development of flame-retardant coatings shows great potential in enhancing the fire retardancy of thermal insulating materials[57-59]. The following instances illustrate the use of nanocellulose fibres in the development of flame-retardant coatings.

-Bio-based fire retardants: The fire retardancy of sustainable insulating material surfaces was improved with the application of coatings consisting of sulfonated kraft lignin, kraft lignin, and nanoclays. The use of microfibrillated cellulose (MFC) as a bio-derived adhesive agent was employed in the formulation of the coating to effectively disseminate and adhere the fire-retardant particles onto the underlying thermal insulating materials. The flammability of the thermal insulating materials covered with a protective layer was assessed by two methods: the single-flame source test and cone calorimetry[57].

-Nanocrystalline cellulose: The research and manufacturing of nanocrystalline cellulose have resulted in the creation of a flame-retardant material that exhibits exceptional thermal insulation properties while also being ecologically sustainable. The preparation of nanocrystalline cellulose was conducted using the process of silylation[60].

-Sodium bicarbonate: Sodium bicarbonate was used in the preparation of CNF aerogels, resulting in boosted fire retardancy while maintaining the rigidity of the aerogels[61].

-Layer-by-Layer (LbL)-functionalized cellulose fibers: In this research, we fabricated low-density and flame-retardant (FR) porous fibre networks by using a layer-by-layer (LbL) approach to functionalize cellulose fibres. The fire resistance qualities of the fibre networks were assessed via the use of a cone calorimeter and a single-flame source test[58].

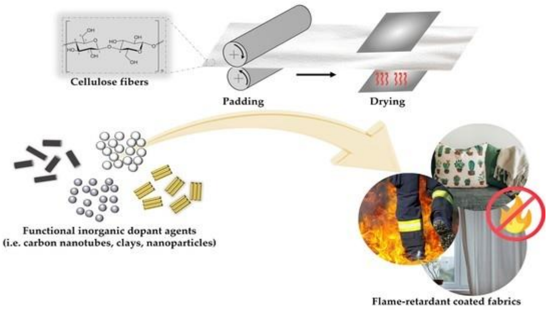

Figure 2. The use of functional inorganic sol-gel precursors and nanofillers in cotton fabrics enables flame-retardant technology[62].

3.II.D UV-resistant coatings

The prospective uses of UV-resistant coatings based on nanocellulose in the field of sustainable textiles have been identified[63, 64]. Nanocellulose, including nanofibrillated cellulose (NFCs), cellulose nanocrystals (CNCs), and cellulose nanowhiskers (CNWs), has the potential to serve as reinforcing fillers in nanocomposites for textile reinforcement[65]. The nanocellulose materials possess many desirable characteristics, including low cost, abundance, lightweight nature, renewability, and nano-scale dimensions. These attributes render them highly appropriate for sustainable textile applications[66]. Added to that, it has been shown that the use of nanocellulose-based coatings may provide effective protection against ultraviolet (UV) radiation for textiles, hence safeguarding them from the detrimental effects of UV radiation[28]. The distinctive characteristics shown by nanocellulose, including its exceptional mechanical strength, biocompatibility, and customizable surface chemistry, render it a very suitable substance for the development of UV-resistant coatings in the realm of sustainable textiles. The integration of nanocellulose into coatings enables the production of sustainable textiles that exhibit improved durability and UV protection. This advancement contributes to the progress of environmentally conscious and sustainable materials.

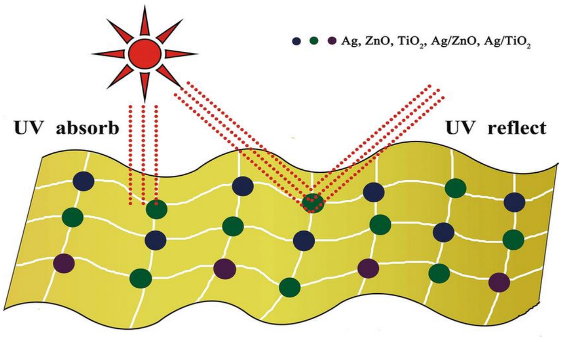

Figure 3. The schematic mechanism of UV protective coating involves the absorption or reflection of ultraviolet (UV) radiation[67].

3.II.E Self-cleaning coatings

The use of self-cleaning coatings in practical textile applications is seeing a growing trend in popularity. These coatings function by inducing a photocatalytic reaction on the fabric using photocatalysts like titanium dioxide and zinc oxide. The efficacy of the self-cleaning effect is enhanced in samples that are coated with greater quantities of TiO_2[68]. Additional components used in the development of self-cleaning coatings include oil palm boiler ash (OPBA), chitosan, and cellulose nanofibers (CNFs)[69-71]. Besides, these coatings include antibacterial, UV-blocking, and persistent scent-release qualities[70]. Zinc oxide has gained significant popularity as a material for functional textile coatings. However, considerable progress has been achieved in the development and analysis of self-cleaning cotton textiles by the use of zinc oxide nanoparticles, which induce photocatalytic degradation[72].

4. Nanocellulose fibers for the development of new sustainable textile materials

4.A Nanocellulose-based aerogels

One recognised use of nanocellulose fibres is related to the advancement of nanocellulose-based aerogels, which exhibit a diverse array of prospective applications across several sectors. Aerogels are materials characterised by their very low density and large surface area, owing to their unique three-dimensional porous structure. The removal of the liquid component of a gel is achieved using a scientific procedure known as supercritical drying. Nanocellulose-derived aerogels provide several benefits in comparison to conventional aerogels, particularly their sustainable nature, biodegradability, and regenerative qualities. Fabric designed from waste cotton, fibres derived from textile waste, and cellulose may be used for this purpose[73-76].

A plausible use of aerogels derived from nanocellulose lies in the advancement of oil absorbents that are both environmentally friendly and capable of repeated use. Floating, sustainable, reusable, and recyclable oil absorbents have been produced in the form of hydrophobic nanocellulose aerogels[75]. The aerogels discussed below are derived from cellulose, a renewable material that may be conveniently disposed of by incineration alongside the oil it has absorbed. Recent work has shown that aerogels made from textile waste fibres have remarkable qualities in terms of oil and organic solvent adsorption, as well as thermal characteristics[74].

Beyond that, researchers have successfully created porous coaxial fibres using nanocellulose aerogels, which exhibit thermal insulation properties[76]. These fibres signify an important milestone in the field of biobased thermal insulating materials, potentially leading to a transformative impact on the development of sustainable insulation materials.

The exploration of new uses of aerogels in textiles has been documented[77]. The integration of aerogels into fabrics does not always result in a reduction in permeability. An instance of the use of silica aerogel-phase change materials may be seen in the development of thermoregulating textiles.

4.B Nanocellulose-based hydrogels

Nanocellulose has distinctive structural characteristics and is considered an essential and plentiful renewable resource in the field of textiles. Advancements in contemporary technologies have facilitated the creation of filaments with exceptional tensile strength, devoid of the need for dissolution or intricate chemical procedures that may be hazardous. Consequently, the development of solvent-free fibres is now poised for commercialization[78].

Efficient carriers for textile dyes have been produced using nanocellulose-based hydrogels, with the aim of reducing environmental contamination caused by effluents released during conventional textile dyeing procedures. The hydrogels used in this study are composed of nanofibrillated cellulose (NFC), a kind of nanocellulose. These hydrogels provide a viable and environmentally friendly substitute for conventional techniques employed in textile dyeing. NFC-based hydrogels possess non-toxic properties and may be fabricated using readily available cellulose sources, thus presenting an ecologically sustainable alternative for textile dyeing[79].

As well, nanocellulose fibres have shown potential applications beyond textile dyeing, including paper and textile coating, as well as the fabrication of film composites[80, 81]. Nanocellulose may be derived from plant fibres or algae, and its efficacy is attributed to its little thermal expansion, as shown by previous research[82].

4.C Nanocellulose-based films

The use of nanocellulose-based films has garnered considerable interest in accelerating the development of environmentally friendly textile products[80, 83]. Nanocellulose, among others, including cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs), has many benefits, including its widespread availability, straightforward production processes, biodegradability, and cost-effectiveness[84]. The earlier-mentioned materials have the potential to serve as substitutes for plastic coatings in the textile industry, hence offering improved strength and performance attributes to fiber-based materials[11]. Its coatings may be customised with certain characteristics, including hydrophobicity, antimicrobial capabilities, and resistance to ultraviolet radiation[85]. Along with this, nanocellulose has promising potential in the realm of stabilising ancient paper and archaeological fabrics. The distinctive physicochemical characteristics shown by nanocellulose, including its exceptional strength, low weight, and transparency, make it a very promising substance for a wide range of practical applications.

4.D Nanocellulose-based nonwovens

There has been a significant surge in interest in nanocellulose fibres as a means of advancing the production of environmentally friendly textile materials, particularly in the domain of nanocellulose-based nonwovens. These fibres provide many benefits, including their ecologically benign nature, biodegradability, and outstanding mechanical qualities. Bioinspired designs enable the fabrication of innovative materials with multifunctional features[86]. Nanocellulose fibres, which are cellulose nanofibrils (CNFs) and cellulose nanocrystals (CNCs), have shown the ability to replicate the structure and functionality of natural plant fibres such as cotton. Another benefit is that these nanocellulose fibres possess adjustable features[65, 87]. The aforementioned fibres possess elevated aspect ratios, exceptional wicking capabilities, and may be readily altered to bestow favourable surface characteristics[45, 80]. The use of nanocellulose-based nonwovens has promise for transforming the textile industry through the provision of environmentally friendly substitutes for conventional materials.

5. Challenges and Future Prospects of Nanocellulose Fiber in Sustainable Textiles

5.I Challenges in the commercialization of nanocellulose fiber for textile applications

The increasing recognition of nanocellulose fibre in the textile industry is attributed to its favourable physical and chemical characteristics, as well as its widespread availability, abundance, and cost-effectiveness[88]. However, the commercialization of nanocellulose fibre for textile applications presents numerous obstacles, such as the manufacturing cost, scalability, dispersibility, and durability of textile matrices.

- Cost of Production

One of the primary obstacles to the commercialization of nanocellulose fibre for textile applications is the financial burden associated with manufacturing expenses. The cost of producing nanocellulose fibres is subject to variation based on the chosen manufacturing technique and the origin of the cellulose material. An instance of a study documented the manufacturing cost of cellulose nanofibers (CNFs) by a sulfuric acid hydrolysis method, amounting to $3.19 USD/kg. This cost is about 70.9 times cheaper compared to the production cost of CNFs utilising TEMPO oxidation[89]. Nevertheless, the manufacturing costs remain higher in comparison to conventional textile fibres like cotton and polyester. Hence, the need for cost reduction in the manufacturing process becomes paramount in order to facilitate the commercialization of nanocellulose fibre for textile applications.

- Scalability

Scalability is another obstacle that must be overcome in order to successfully commercialise nanocellulose fibre for use in textile applications. While the present production of nanocellulose on an industrial scale has reached several tonnes per day, its manufacturing capacity remains constrained when compared to that of conventional textile fibres[90]. Thus, it is essential to establish scalable manufacturing techniques in order to effectively fulfil the growing demand for nanocellulose fibre within the apparel and textile industries.

- Dispersability

The issue of dispersability is an important limitation in the process of commercialising nanocellulose fibre for textile uses. Aggregates of nanocellulose fibres are often seen as a result of their elevated surface area and robust bonding of hydrogen between molecules. As a consequence, the attainment of favourable dispersibility of nanocellulose fibres in aqueous solutions and other solvent systems is of paramount significance in order to facilitate their effective utilisation in textile-related contexts. Various techniques have been devised to enhance the dispersibility of nanocellulose fibres, including mechanical fibrillation, chemical modification, and surface functionalization[91].

- Durability in Textile Matrices

The issue of durability in textile matrices is a major hurdle in the industrialization of nanocellulose fibre for textile purposes. Nanocellulose fibres are affected by deterioration when exposed to moisture, heat, and UV light[41]. Because of this, it is essential to boost the longevity of nanocellulose-based fibres within textile composites to ease their use in practical applications. Several methods have been designed to enhance the longevity of nanocellulose fibres inside textile matrices. These approaches include crosslinking, coating, and amalgamation with other fibres[88].

To tackle these problems, it is necessary to focus on finding ways to accelerate the development of scalable and economically feasible manufacturing techniques, enhance the dispersibility and longevity of nanocellulose fibres, and investigate novel uses and markets for nanocellulose fibres within the textile industry itself.

5.II Future prospects for the development of new and innovative nanocellulose fiber-based textiles

5.II.A Development of new and improved nanocellulose fiber production methods

It is anticipated that the next advancements in nanocellulose fibre manufacturing techniques will mostly concentrate on enhancing current technologies and investigating novel sources and uses for this very promising material. Several crucial domains of development encompass:

Emerging technologies: Modern techniques are being studied by researchers to develop fresh methods for the production of nanocellulose from lignocellulosic biomass. One such technique is the top-down process, which entails the fragmentation of cellulose fibres derived from lignocellulosic sources into nano-sized particles[92].

Functionalization: The enhancement of characteristics and performance in nanocellulose-reinforced polymer composites is expected to require the process of functionalization[15].

New sources and methods: The incorporation of new sources and methodologies It is anticipated that the identification and development of new sources and techniques for the synthesis of nanocellulose will persist as research and innovation progress[93].

Techno-economic considerations: Techno-economic factors are of paramount importance in assessing the financial stability and long-term sustainability of emerging nanocellulose manufacturing techniques. Economic research and empirical case studies are important in this evaluation process[93].

Nanocellulose-based biomaterials: The advancement of nanocellulose-based biomaterials, exhibiting diverse features and applications, is anticipated to propel research and development endeavours in this domain[7].

Processing methods: The investigation of novel processing techniques, such as solution casting and melt processing, for the production of nanocellulose-based nanocomposites is expected to facilitate the broadening of nanocellulose applications[90].

Modification: The pursuit of innovative applications and enhancement of attributes in nanocellulose-based materials remains a major priority in the field of research and development, as shown by previous studies[90].

5.II.B Development of new nanocellulose fiber-based composites with enhanced properties

The evolution of nanocellulose fiber-based materials with better properties necessitates the resolution of existing restrictions associated with nanocellulose fibres, as well as the exploration of novel applications for these materials. Several noteworthy areas of attention include:

The features of nanocellulose may be modified to address certain limitations. One such limitation is the presence of several hydroxyl groups, which contribute to the gel-like structure of the product. Also, the high hydrophilicity of nanocellulose restricts its potential uses[65]. Scholars have the potential to enhance the properties of nanocellulose and broaden its applications in natural fibre utilisation through modification efforts.

Nanocellulose-based alloys demonstrate excellent biocompatibility and biodegradability, making them suitable for use as biologic materials[15]. Despite this, there is potential for enhancement in both the biodegradability and mechanical qualities of the aforementioned materials.

The field of nanocellulose-reinforced polymer composites is now undergoing extensive research efforts aimed at improving the tensile strength and biocompatibility of these materials[94].

The use of advanced nanocellulose-based composites is now being investigated for its potential application in flexible functional energy storage devices. These composites provide many advantages, including their persistent availability, unparalleled properties, and distinctive architectures[95].

The utilisation of nanocellulose fiber-reinforced starch biopolymer composites is increasingly being pursued in light of the renewable nature, widespread accessibility, and biodegradability of starch[3]. These composite materials have shown substantial improvements in mechanical, barrier, and heat characteristics.

These technological developments will facilitate the substitution of conventional plastic composite materials with more sustainable and ecologically sound alternatives.

5.II.C Development of new nanocellulose fiber-based functional coatings for textiles

Functional textile coatings based on nanocellulose fibres have been the focus of current innovation and research. The newest scientific investigations have yielded significant progress in the discipline of nanocellulose-based coatings for paper and textiles, underscoring the criticality of surface chemistry[80]. Subsequent investigations need to prioritise the augmentation of the interfacial adhesion between nanocellulose fibres and non-polar polymers by means of inventive and green sustainable approaches[41]. The investigation of the adherence and durability of nanocellulose coatings on flat polymer films and textiles has been conducted, revealing that this technique for functionalizing natural and synthetic fibres and fabrics is ecologically sustainable while also maintaining their compostability[96]. The literature also addresses the advancement of nanocellulose-based nanocomposites for sustainable applications, and it is evident that materials derived from nanocellulose have great potential for the creation of high-quality, eco-friendly functional materials in the future[65].

5.II.D Development of new nanocellulose fiber-based sustainable textile materials

The potential for addressing worldwide ecological concerns and offering fresh performance is significant in the future development of durable textile materials based on nanocellulose fibres. The fabrication of fibres with competitive qualities compared to high-performance synthetic fibres, as well as regulated and predictable properties, may be achieved by the spinning of filaments derived from nanocellulose[84]. The investigation of several approaches to enhance the porosity of carbon fibres derived from nanocellulose has been undertaken, leading to improvements in both specific surface area and total pore volume[97]. The use of green composites based on nanocellulose has become more popular due to its advantageous properties, such as their lightweight nature, affordability, and impressive mechanical and physical attributes. Consequently, these composites have shown promising potential for many applications in the biomedical and engineering sectors[7]. Moreover, the incorporation of nanocellulose optical waveguides into yarn architectures has shown the potential for developing environmentally friendly smart textiles that include optical sensing functionalities[98]. In general, the prospective advancement of sustainable textile materials based on nanocellulose fibres has promising prospects for innovation and the resolution of sustainability issues.

Conclusion

The use of nanocellulose fibre in sustainable textiles has great promise owing to its distinctive characteristics, including exceptional mechanical strength, elevated aspect ratio, and reduced density. The use of nanocellulose fibre in the textile manufacturing sector has the potential to mitigate the environmental consequences associated with the industry via the utilisation of sustainable resources and waste reduction. Nevertheless, there are some obstacles that need attention, including the considerable abundance of hydroxyl groups present in nanocellulose fibre. This abundance contributes to the gel-like nature of the product's structure and its pronounced hydrophilic properties, hence imposing limitations on its potential applications. Future research and development endeavours should prioritise the resolution of these issues and the enhancement of the characteristics of nanocellulose fibre, with the aim of optimising its suitability for use in environmentally friendly textiles. Furthermore, more research is required to examine the possibility of nanocellulose fibre derived from microbial and plant origins as a viable alternative for textile fibres. In general, the use of nanocellulose fibre in the context of sustainable textiles exhibits significant promise and justifies the need for more research and exploration.

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