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Functional Nanocellulose Derivatives for Global Environmental Solutions

Rini Perdana *

Department of Chemistry, Faculty of Mathematics and Natural Science, Makassar State University, Indonesia

*Email (corresponding author): rini.perdana@unm.ac.id

Abstract

Nanocellulose, a sustainable and biodegradable material derived from natural cellulose, holds immense potential for addressing global environmental challenges. This article reviews the production methods, structural modifications, and applications of nanocellulose derivatives in environmental contexts, emphasizing their role in water purification, pollutant adsorption, and renewable energy solutions. The systematic literature review highlights the unique properties of nanocellulose, such as high mechanical strength, large specific surface area, and tunable chemical functionalities, which enable its use in various industrial, biomedical, and environmental applications. Results indicate that nanocellulose-based materials outperform conventional materials in efficiency and sustainability, particularly in water treatment and biodegradable packaging. Despite its advantages, challenges remain, including production costs, dispersibility in polymer matrices, and stability under high humidity. These limitations necessitate further research and collaborative innovation to enhance its applicability and affordability.

Keywords: *Nanocellulose, NCT, environmental, sustainability water purification*

1. Introduction

In recent decades, there has been a notable rise in global focus on environmental issues, prompting a quest for innovative solutions to our planet's challenges. A notable strategy in this area involves the utilization of nanocellulose, a cellulose derivative that possesses distinctive properties and significant potential for environmental applications. Nanocellulose, derived from diverse sources such as plants, animals, and bacteria, presents substantial benefits related to sustainability, biodegradability, and effectiveness across numerous applications, including water purification, food packaging, and the development of pollutant sensors (1–4). As the demand grows to mitigate the environmental consequences of traditional materials, nanocellulose is becoming a promising alternative to plastic-based substances and other harmful chemicals. A key feature of nanocellulose is its biodegradability, rendering it a compelling substitute for synthetic materials that pose challenges in terms of degradation.

Nanocellulose encompasses several forms, such as cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), and bacterial cellulose, each exhibiting distinct physical and chemical properties (5–7). The distinctive composition of nanocellulose positions it as an optimal material for incorporation into composites and membranes, enhancing efficacy in environmental applications like water filtration and the creation of sustainable materials (2,6,8). Recent findings indicate that nanocellulose can function not only as a filling material

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but can also be altered to enhance its functionality, including applications in creating membranes for pollutant separation and sensors (2,3,8).

Moreover, nanocellulose exhibits impressive mechanical strength, with Young's modulus values that rival those of steel, positioning it as a remarkably strong and flexible material suitable for various applications (9,10). Nanocellulose presents significant opportunities for advancing renewable energy technologies. In this context, nanocellulose serves as a matrix in composites for energy devices, presenting a more cost-effective and efficient alternative to traditional materials (1,8). Consequently, additional exploration and advancement in nanocellulose may lead to more sustainable and innovative approaches to address global environmental issues, such as minimizing plastic waste and mitigating water pollution.

The remarkable mechanical properties of nanocellulose arise from its distinctive structure, characterized by nanofibers exhibiting a high degree of crystallinity. Nanocellulose possesses the capability to enhance other materials, including polymers, thereby augmenting the mechanical properties of the end product (11–13). Studies indicate that incorporating nanocellulose into composites enhances tensile strength, elasticity, and resistance to deformation, positioning it as an optimal option for use in packaging, textiles, and construction materials (14,15).

The ability to modify the surface of nanocellulose is a significant factor that enhances its application across multiple domains. Techniques for chemical modification, including esterification and amidation, enable the customization of nanocellulose surface properties to enhance interactions with the polymer matrix or to incorporate specific functionalities, such as antimicrobial properties (16–18). The modifications enhance the compatibility of nanocellulose with various materials and broaden its potential applications, particularly in the biomedical and filtration sectors (18–20).

This article reviews the latest developments in the application of nanocellulose derivatives for global environmental solutions. This study will delve into different production methods, modifications, and applications of nanocellulose within an environmental framework, while also addressing the challenges and opportunities that may arise in the future. This article seeks to enhance understanding of the potential applications of nanocellulose as a functional material for sustainable environmental solutions by synthesizing insights from various recent studies.

2. Methods

This article uses a systematic literature approach to collect, analyze, and synthesize information from various studies related to nanocellulose derivatives and their applications for environmental solutions. This method is designed to provide a thorough overview of the topic through critical analysis of relevant literature

3. Results and Discussion

3.1. Nanocellulose: Characteristics and Classification

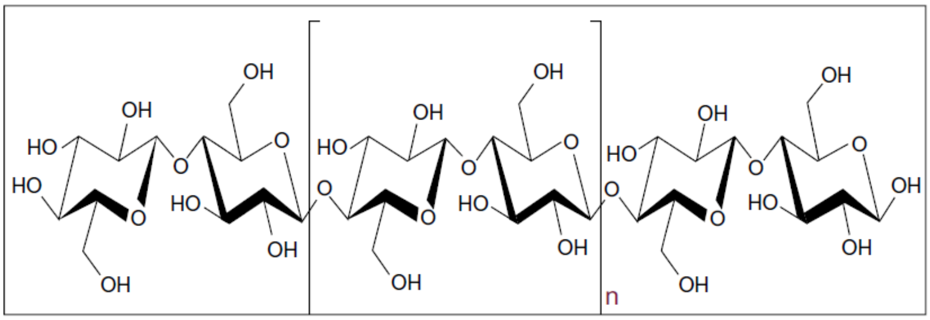

Figure 1. The chemical structure of cellulose, which is a linear polymer made up of β-D-glucopyranose units covalently linked with (1–4) glycosidic bonds

Glucopyranose features three hydroxy groups per anhydro glucose, contributing to the high degree of functionality observed in cellulose. Cellulose is a naturally occurring biopolymer that is abundant, renewable, biodegradable, and non-toxic. Cellulose and its derivatives, as a renewable material, present a valuable opportunity for in-depth study. For over 150 years, cellulose-based materials have found extensive use across diverse applications, including food, paper production, biomaterials, and healthcare (21). The chemical structure of cellulose (Figure 1) illustrates that the polymer created through condensation is composed of monomers connected by glycosidic oxygen bridges (22).

Plants serve as a promising source of cellulose due to their widespread availability in nature (Table 1) (8). The cellulose content in plants typically ranges from 40% to 60%. The overall mass of the plant. In addition to its applications in paper and packaging, cellulose can be employed in the form of nanoparticles. The crystalline fraction in the cell wall originates from cellulose, whereas the amorphous fraction is derived from lignin and hemicellulose. In addition to its presence in plants, cellulose is also observed in various bacteria and tunicates. (23).

Table 1. Various sources for the production of cellulose fibers (8)

Source Group	Source
Hardwood	Eucalyptus, Aspen, Balsa, Oak, Elm, Maple, Birch
Softwood	Pine, Juniper, Spruce, Hemlock, Yew, Larch, Cedar
Annual plants/Agricultural residues	Oil palm, Hemp, Jute, Agave, Sisal, triticale straw, soybean straw, Alfa, Kenaf, Coconut husk, Begasse, Corn leaf, Sunflower, Bamboo Canola, Wheat, Rice, pineapple leaf and coir, Peanut shells, Potato peel,

	Tomato peel, Garlic straw residues, Mulberry fiber, Mengkuang leaves
Animal	Tunicates, Chordata, Styela clava, Halocynthia roretzi Drasche
Bacteria	Gluconacetobacter,, Salmonella, Acetobacter, Azotobacter, Agrobacterium, Rhizobium, Alkaligenes, Aerobacter, Sarcina, Pseudomonas, Rhodobacter
Algae	Cladophora, Cystoseria myrica, Posidonia oceanica

Nano-sized cellulose encompasses cellulose nanocrystals (CNC), cellulose nanofibers (CNF), and bacterial cellulose (BC), each possessing distinct dimensions, characteristics, preparation methods, and applications. Nanocellulose possesses a wealth of hydroxyl groups that are readily amenable to modification. Frequently employed techniques include covalent bonding, chemical modification, and polymer grafting (24). The high specific surface area of nanocellulose presents a significant advantage, particularly in its application for wastewater treatment. Enhancing the specific surface area of nanocellulose can lead to greater interaction with the surrounding matrix, which may subsequently boost the adsorption capacity of nanocellulose-based materials for trapping pollutants and improve the size exclusion capability for eliminating unwanted materials (25).

Cellulose nanocrystals (CNC) are nanomaterials derived from cellulose, a natural polymer present in plants and the primary constituent of plant cell walls. CNC exhibits remarkable mechanical properties, is biodegradable, and possesses a substantial specific surface area. This material exhibits significant potential across various applications, spanning from materials science to biomedical fields, attributed to its excellent biocompatibility, robust mechanical properties, adaptable surface chemistry, and notable optical characteristics (26). The process involves isolating and eliminating the amorphous component of the cellulose fiber, resulting in the retention of its minuscule crystalline portion, typically measuring less than 100 nanometers in diameter (27).

The crystal structure of cellulose nanocrystals (CNC) exhibits distinctive features that are crucial for comprehending its properties. CNC consists of minute crystals known as cellulose nanocrystals, characterized by their extremely small particle sizes, generally ranging from 5 to 50 nanometers in diameter and extending several millimeters in length. Cellulose nanocrystals are composed of nanometer-sized crystalline domains along with amorphous regions, which impart unique mechanical and chemical properties to this material (17). Summarized these physical properties of nanocellulose as listed in Table 2.

Table 2. Physical comparison between nanocellulose (26)

Type of Nanocellulose	Polymerization Rate	Crystallinity/Crystalline Structure
Bacterial nanocellulose (BNC)	4000-10,000	Iα (shell) dan Iβ (inti) - highest degree of crystallinity
Cellulose nanofiber (CNF)	≥500	Especially Iβ - lowest level of crystallinity
Cellulose nanocrystals (CNC)	500-15,000	Especially Iβ, sometimes Iα - medium degree of crystallinity

The diminutive particle size of CNC results in an extensive specific surface area, influencing its characteristics like reinforcement capacity in composite materials and its applications in the biomedical field. The ordered crystal structure of CNC contributes to the material's high mechanical strength. The mechanical properties of CNC are outstanding, featuring high tensile strength and a notable modulus of elasticity, which positions it as a highly desirable material for a range of engineering applications (28)

Furthermore, comprehending the thermal properties of CNC is crucial. CNC exhibits stable and heat-resistant thermal properties, rendering it appropriate for applications that demand resistance to elevated temperatures. Investigations employing thermal analysis methods like thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) aim to elucidate the thermal characteristics of CNC derived from date tree truCNC (29). The consistent thermal characteristics of CNC position it as a promising material for a range of applications that require high-temperature performance.

The chemical properties of CNC significantly influence their applications. Cellulose nanocrystals possess a surface chemistry that can be tailored, enabling modifications to align with particular application requirements. The chemical properties of CNC facilitate surface functionalization, enhancing interfacial interactions with polymer matrices in composites and allowing for the binding of active molecules in biomedical applications (30). The investigation conducted by Yan et al. revealed that CNC derived from corncob acid hydrolysis residue exhibits a type I crystal structure along with a high crystallinity index, suggesting enhanced chemical properties.

The crystalline structure of cellulose nanocrystals or nanocrystalline. Cellulose arises from the atomic arrangement at the nanometer scale, resulting from the extraction of amorphous elements from cellulose fibers. This leads to the formation of crystals characterized by a meticulously organized arrangement of atoms, often on a diminutive scale, generally with a diameter of under 100 nanometers. This structure imparts distinctive physical and chemical properties to NCC. Key characteristics of NCC encompass (12,31):

- Particle Size: NCC has nanometer particles, typically with lengths ranging from a few hundred nanometers to a few micrometers and diameters less than 100 nanometers, which contributes to its high aspect ratio and large specific surface area.
- Mechanical Strength: NCC is known to have high tensile strength, even greater than steel on a per weight basis, which makes it a good candidate for reinforcing material in composites.

- Thermal Properties: Although NCC has lower thermal stability compared to its native cellulose due to its small particle size, it still has enough resistance for applications where moderate thermal stability is required.
- Chemical Properties: NCC is a hydrophilic material due to the presence of hydroxyl groups on its surface, but chemical modifications can be used to tailor its surface properties, such as making it hydrophobic or providing additional functionality (15,32). The crystal is a reference to native cellulose. After deconvulation all the diffractograms showed 2θ reflections 14.5-15.3o which is the crystal plane (110), 2θ reflections 15.7o - 16.30o which is the crystal plane (110), 2θ reflections = 21.90o and 22.20o which is the crystal plane 200 and 2θ reflections 18.30o -18.40o which is the amorphous phase.

CNC typically originates from biomass sources, including wood, plants, or various plant fibers. The production process of CNC encompasses various techniques, such as acid hydrolysis, enzymatic hydrolysis, and TEMPO oxidation, all designed to break down cellulose into small crystals at the nanometer scale. For example, in (33) study they isolated and produced cellulose nanocrystals from Conocarpus fibers, showing that different cellulose sources can be used to produce CNC. Methods for producing CNCs include (34): Acid hydrolysis; Ionic hydrolysis, Liquid threat; Deep eutectic solvent; Enzymatic hydrolysis; Organo solvent threat; TEMPO oxidation; Mechanical method; Electron beam irradiation. The properties of CNC mainly depend on the cellulose source and extraction process (35).

The process of acid hydrolysis is a widely utilized method for the production of CNC. A study demonstrated the use of acid hydrolysis to extract lignin from wood, leading to an improvement in enzymatic cellulose hydrolysis. This process improves the hydrolysis of cellulose through enzymatic action, leading to the formation of nanometer-sized cellulose crystals (36). Furthermore, a study indicated the exceptional characteristics of CNC, such as biodegradability, commercial availability, printability, low density, high porosity, optical transparency, along with remarkable mechanical, thermal, and physicochemical properties (19).

Besides acid hydrolysis, alternative methods for producing CNC include the application of ionic liquid. The manufacturing process of cellulose particles involves the use of ionic liquid, wherein water-dispersed cellulose particles are subjected to immersion in liquid nitrogen followed by freeze-drying. This method yields cellulose particles suitable for a range of applications (37). With various production methods available, CNC can be produced from different cellulose sources and used in a variety of innovative applications (Figure 2).

The NCC production process involves a few basic steps:

- Pre-treatment: Natural cellulose from sources such as wood or other plant fibers is given chemical or mechanical treatment to clean and prepare it for the next process.
- Acidification: The cleaned cellulose is soaked in acid, such as sulfuric acid or hydrochloric acid, to remove the amorphous parts and strengthen the crystalline structure present in the cellulose.
- Leaching: The cellulose crystals formed are washed to remove any residual acid and unwanted chemicals.

- Homogenization: The acidified cellulose fibers are homogenized, either by physical methods such as ball milling or by high-pressure homogenization, to produce nanocrystal particles of uniform size.
- Separation: Solutions containing NCC can be separated and concentrated to obtain the final product in the form of NCC suspension or powder. (2,27,38).

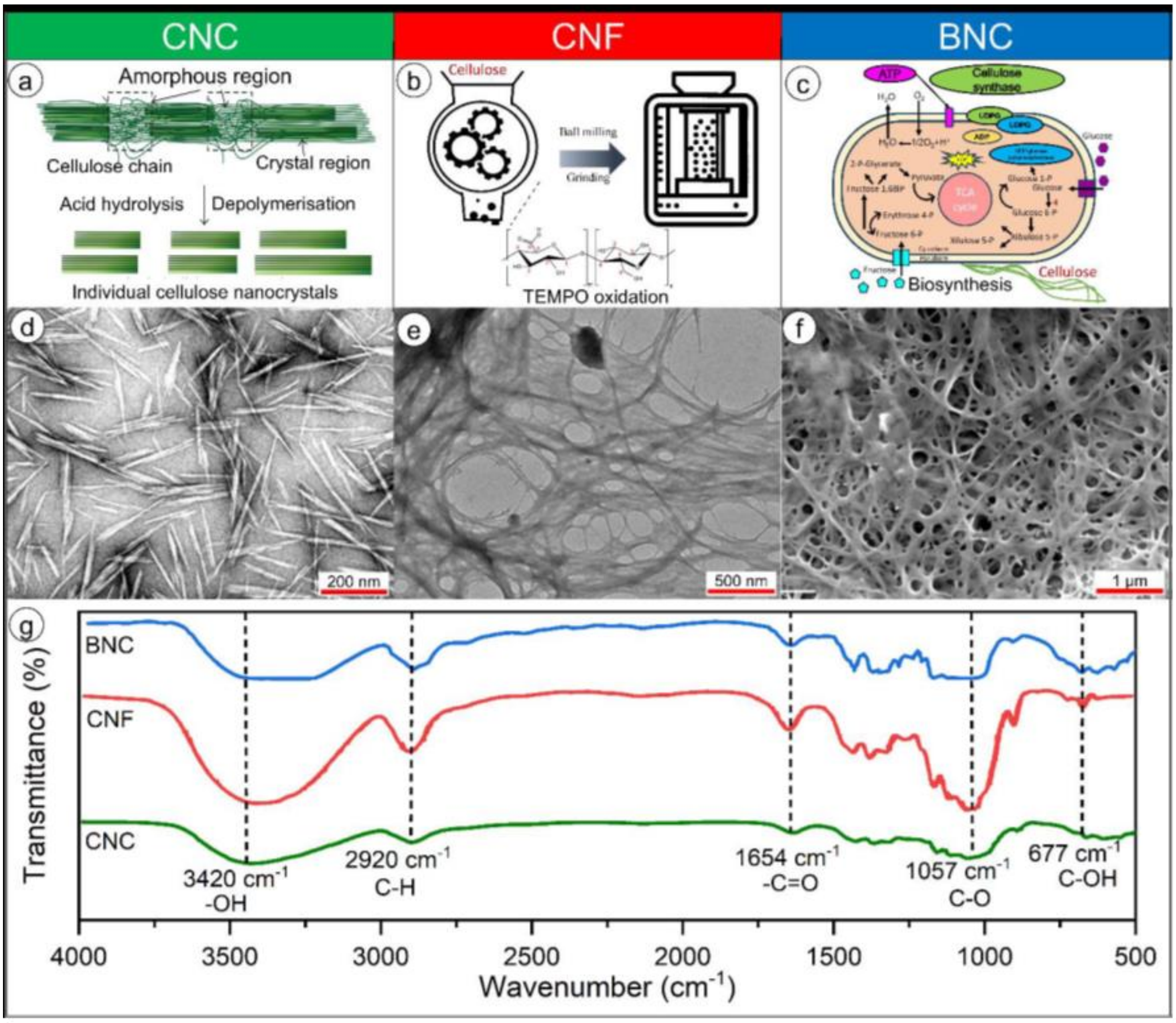

Figure 2. Schematic illustrations of preparation processes of CNC (a), CNF (b) and BNC (c); TEM images of CNC (d), CNF (e), and FESEM image of BNC (f); FTIR spectra (g) for CNC, CNF and BNC.

3.2. Applications of Nanocellulose Derivatives in Environmental Solutions

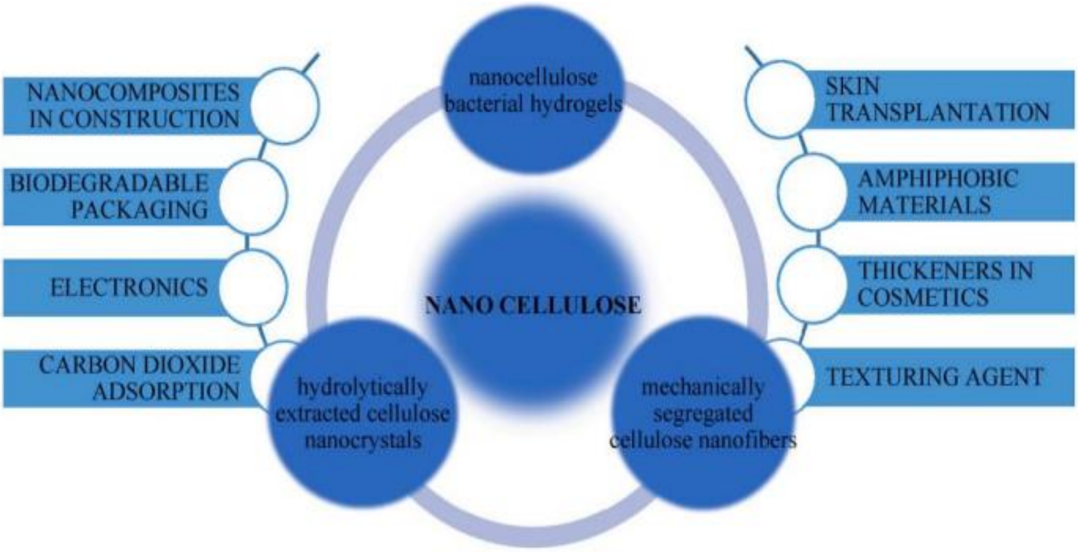

Figure 3. Nanocelulose applications

The study of nanocellulose materials encompasses not only their synthesis from plant sources but also explores their potential applications across various fields (Figure 3). The distinct characteristics of nanocellulose paper include its transparency, flexibility, and impressive mechanical strength. The characteristics of nanocellulose paper facilitate its application in solar cells, displays, and electronic circuits. The paper exhibits remarkable strength and can withstand a pressure of 223 MPa, possesses an elastic modulus of 13 GPa, and demonstrates a minimal thermal expansion of 8.5 ppm K^{-1} (39). These properties enable the use of nanocellulose paper in the production of electronic devices and gadgets.

Nanocellulose materials can be utilized in medicine because they exhibit excellent biocompatibility with human and mammalian organ tissues. Studies have demonstrated the use of bleached birch nanocellulose as a wound dressing, highlighting its favorable biocompatibility with skin tissue (40). The nanocellulose dressing can adhere well to the wound and easily peel off after skin repair (41). Recent years have seen the exploration of other applications of nanocellulose in medicine, including targeted drug delivery, soft tissue implants, and blood vessel replacement. Furthermore, regarding the practical applications of nanocellulose, it is noteworthy that nanocellulose materials are utilized in the cosmetics business, serve as stabilizers in the food sector, and function as carbon dioxide absorbers, among other purposes. Nanocomposites composed of nanocellulose have unique characteristics, including elevated mechanical strength coupled with low material density, in addition to thermal stability. Owing to these characteristics, nanocellulose can be utilized in several sectors of human endeavor, such as the manufacture of materials for agriculture, heavy machinery, manufacturing, and military technologies (42–44).

Nanocellulose has proven effective in water treatment, especially through membrane technology. Nanocellulose-based membranes are capable of filtering particles and solutes at the nanometer scale, producing clean water with high efficiency. Some specific applications include:

- Water FiltrationNanocellulose membranes can remove heavy metals and organic matter from wastewater with very high levels of efficiency. For example, the use of nanocellulose composite membranes can achieve retention rates of up to 99% against certain contaminants(36).

- Pollutant Adsorption: Nanocellulose can serve as an adsorbent to bind heavy metals such as lead (Pb) and cadmium (Cd) from water, aiding in the remediation process (16).
- Use in Nanosensor Technology: Nanocellulose-based nanosensors can be used to detect low concentrations of polluting substances in soil and water, enabling real-time monitoring of environmental quality (45)

Nanocellulose also plays an important role in environmental remediation through several mechanisms:

- As a Flocculant: Nanocellulose can be used to precipitate small particles in water, helping to reduce turbidity and improve water quality.
- Photocatalysis: In several studies, nanocellulose has been used as a photocatalyst material for the degradation of organic pollutants under sunlight. This shows the potential of nanocellulose in breaking down harmful compounds into harmless products.
- Bioremediation: With its biodegradability, nanocellulose can be used as a base material to support the growth of microorganisms that function in the bioremediation process of polluted soil.

Recent years have witnessed an increasing interest in NC and CNT composites, owing to their potential uses in the energy sector. The unique properties of CNTs make them an excellent choice for improving electrical conductivity in non-conductive nanocellulose templates through coating or blending methods. While a direct application of carbon nanoparticles enhances conductivity in NC films relative to polymer films, merely augmenting thickness or layering often fails due to insufficient adherence of carbon particles. This problem results in delamination (45). Unlike surface coating, mixing enables a deeper infiltration of carbon particles into the substrate, as the NC substrate adeptly holds a significant quantity of particles. The use of a nanocellulose template infused with a continuous network of carbon materials facilitates the production of conductive composites that demonstrate elevated electrical conductivity as well as remarkable tensile and bending durability. The consistent incorporation of CNTs or graphene with nanocellulose fibers as a matrix promotes channel development and enables unlimited ion transport, successfully mitigating the challenge of low dispersibility of carbon nanomaterials resulting from their hydrophobic properties (41). This, in turn, gives supercapacitors excellent charge and discharge rates and helps reduce the volume change of electrode materials in various pseudocapacitive reactions.

Table 3. Influence of various sources of raw materials on the properties of CNC (44–46)

CNC source used	CNC selection method	Crystallinity index, %
Miscanthus giganteus	Acid hydrolysis	76
Miscanthus giganteus	Two-stage heat treatment	76.5
Miscanthus giganteus	Acid hydrolysis	78
Miscanthus lutarioriparius	Acid hydrolysis	74.7
Miscanthus giganteus	Alkaline hydrolysis, bleaching, acid hydrolysis	>90
Miscanthus floridulus	Acid gydrolysis	76.53
Post-harvest tomato plant residue	Acid hydrolysis	78-89
Juncus (Juncaceae)	Acid hydrolysis	81-83
Waste paper	Acid hydrolysis,oxidation with ammonium persulfate	72.45-77.56
Sugarcane straw	Acid hydrolysis	62.66
Pineapple crown fibers	Acid hydrolysis	73
Pea hull	Acid hydrolysis	77
Lagenaria siceraria peels	Bleaching and acud hydrolysis	83

Among all oxidation-mediated nanocellulose, periodate oxidation-mediated nanocellulose (PONC) has demonstrated significant potential and has been thoroughly studied in recent years. The oxidation of cellulose using sodium periodate in an aqueous environment leads to the transformation of vicinal diol groups into dialdehyde groups. The reactivity of these aldehyde groups surpasses that of carboxylate groups (30) This compound can be readily transformed into a range of functional groups. PONC has proven to be an effective adsorbent or flocculant agent for water treatment through meticulous adjustments of its surface groups and charge density. The subsequent sections will concentrate on its utilization in the elimination of heavy metals and organic dyes, as outlined in Table 4.

3.3. Challenges in the use of Nanocellulose

Although nanocellulose presents numerous benefits as a sustainable material, its application encounters several notable obstacles. A significant challenge lies in the efficient and cost-effective production and processing of nanocellulose. The extraction of nanocellulose from lignocellulosic sources frequently involves hazardous chemicals and significant energy consumption, potentially compromising the sustainability and environmental integrity of these materials (47). Furthermore, while nanocellulose exhibits significant potential across numerous applications, the elevated production costs remain a substantial barrier to its broader implementation within the industry (32,48).

A significant challenge encountered by nanocellulose involves its dispersibility within polymer matrices. Nanocellulose exhibits significant hydrophilic characteristics, leading to its tendency to aggregate in non-polar solvents or hydrophobic polymer matrices, consequently diminishing its efficacy as a reinforcing agent in composites (49,50). The integration of nanocellulose into plastic or other polymer-based products presents challenges, particularly when a strong interaction between nanocellulose and the matrix is crucial for achieving optimal performance (51,52).

Moreover, nanocellulose encounters obstacles concerning its stability and resistance to moisture. While nanocellulose exhibits excellent biodegradability, its moisture resistance may influence the effectiveness of the material in specific applications, including food packaging and construction materials (11,53). Elevated humidity levels can lead to a reduction in the mechanical properties and stability of nanocellulose, potentially restricting its application in moist conditions (40).

Another challenge to examine is the potential toxicity and reactivity of nanocellulose. While nanocellulose is typically regarded as safe and biocompatible, alterations in its chemical structure aimed at enhancing surface characteristics and functionality could potentially influence its toxicity and interactions with biological systems (54,55). Consequently, it is crucial to pursue additional investigations to comprehend the lasting effects of employing modified nanocellulose in biomedical and environmental contexts (56,57).

Ultimately, the challenges posed by regulation and industry standards are significant factors affecting the adoption of nanocellulose. As an emerging material, nanocellulose remains unregulated in numerous jurisdictions, potentially leading to uncertainty for both manufacturers and end-users (58,59). Establishing clear guidelines and standards for the application of nanocellulose is essential for promoting its adoption and ensuring its safe utilization (60,61).

In summary, although nanocellulose presents considerable promise as a sustainable material, it is essential to tackle these challenges through advancements in its production, modification, and application methods. In-depth investigation and partnership among educational institutions, businesses, and regulatory bodies will be essential for enhancing the application of nanocellulose and fully realizing its advantages for both the environment and society.

Conclusions

In light of numerous challenges, nanocellulose continues to present significant potential for future applications. Nanocellulose exhibits multifunctional and environmentally friendly properties, showcasing significant potential for diverse applications, including water treatment and renewable energy. Joint initiatives among educational institutions, businesses, and regulatory bodies are essential to address these challenges and guarantee that nanocellulose can realize its complete potential in developing sustainable solutions for an improved world.

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Conflicts of Interest

The authors declare no conflict of interest.

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