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MINI REVIEW

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Cellulose nanofibers for sustainable water filtration applications

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ABSTRACT

Water pollution has become a global concern due to the continuous discharge of industrial effluents, agricultural runoff, and pharmaceutical residues into aquatic bodies, causing serious risks to both environmental and human health. Traditional water treatment methods, including chemical precipitation, membrane filtration, and biological processes, have limitations, including high operational costs, incomplete removal of emerging contaminants, and the generation of secondary pollutants. Due to these limitations, the use of bio-based nanomaterials is gaining attention for combining high performance with ecological safety.

Cellulose nanofibers (CNFs) have emerged as promising nanomaterials derived from lignocellulosic biomass and agro waste. CNFs have unique physicochemical properties, including high surface area, nanoscale dimensions, high mechanical strength, and reactive hydroxyl groups that facilitate surface modification. These characteristics make CNFs highly suitable for water filtration applications, where they can effectively remove a wide range of pollutants through processes such as adsorption, electrostatic interaction, and chemical complexation. Recent studies further prove that CNF-based composite filters, including those integrated with natural materials such as clay, can efficiently remove antibiotic contaminants from wastewater. But the practical application

The use of CNFs in large-scale water treatment remains restricted due to limited scalability, variability in raw material sources, and challenges with long-term stability and regeneration. The objective of this mini-review is to examine recent developments in the preparation, characterization, and application of CNFs for sustainable water filtration, with a focus on their mechanisms of pollutant removal.

KEY WORDS

Cellulose nanofibers; Lignocellulosic biomass; Bio-based nanomaterials; Membrane filtration; Antibiotic contaminants

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Introduction

Water pollution has emerged as a major environmental challenge of the century, due to rapid industrialization, urbanization, and intensified agricultural practices. The discharge of untreated or partially treated effluents containing heavy metals, synthetic dyes, pesticides, and pharmaceutical residues into water bodies has reduced water quality. Among these contaminants, emerging pollutants such as antibiotics are the most significant due to their persistence in aquatic environments [1]. A substantial fraction of antibiotics is discharged unmetabolized, leading to their accumulation in wastewater streams and environmental pollution. This growing concern of contaminants requires the development of efficient, sustainable, and economically viable water treatment technologies [2].

Traditional water purification techniques, including coagulation–flocculation, membrane filtration, advanced oxidation processes, and biological treatments, have been widely used for water treatment. However, these methods have limitations, such as high operational and maintenance costs, incomplete removal of contaminants, energy-consuming processes, and the generation of secondary pollutants, such as sludge [3]. Also, their efficiency in removing low-concentration contaminants, such as pharmaceutical residues, remains questionable. As a result, there is an increasing demand for innovative methods that overcome these challenges.

Nanotechnology has enabled advanced solutions for environmental remediation, particularly in water treatment. Nanomaterials, due to their high surface area-to-volume ratio, enhanced reactivity, and tunable physicochemical properties, have represented superior performance in pollutant removal compared to traditional materials. However, many inorganic and synthetic nanomaterials raise concerns about toxicity, non-biodegradability, and environmental persistence, which limit their widespread application [4]. Hence, research has increased toward the development of bio-based, sustainable nanomaterials that combine high efficiency with minimal environmental impact.

CNFs have gained significant attention as eco-friendly nanomaterials for water purification. Derived from lignocellulosic biomass such as wood, agricultural residues, and plant fibers, CNFs are the most sustainable nanomaterials. Their production from agro-waste materials, including banana fibers and other lignocellulosic residues, helps reduce environmental waste and provide a cost-effective raw material source. Structurally, CNFs consist of nanoscale fibrils with diameters below 100 nm and high aspect ratios [5]. Additionally, the presence of hydroxyl groups on their surface facilitates chemical modification, allowing functional groups such as carboxylates to enhance adsorption capacity and interactions with pollutants.

The synthesis of CNFs is performed through different mechanical, chemical, and combined methods. TEMPO-mediated oxidation has emerged as a highly efficient and environmentally friendly method for selectively adding carboxyl groups to cellulose surfaces under mild aqueous conditions. This process helps produce nanofibers with uniform dimensions and improved dispersibility, thereby enhancing their performance in filtration applications [3]. Acid hydrolysis and enzymatic treatments have also been used to produce CNFs with

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properties suitable for environmental applications.

A literature review highlights the potential of CNFs for water and wastewater treatment. Their application spans multiple mechanisms, including adsorption of heavy metals via electrostatic interactions, removal of organic pollutants, and filtration of microbial contaminants. The high surface area and porosity of CNF-based materials contribute to their adsorption efficiency. At the same time, their ability to form interconnected porous networks makes them suitable for membrane-based filtration systems [6]. Recent studies have demonstrated the effectiveness of CNF-based composite materials, such as CNF–clay filters, for removing pharmaceutical contaminants, including antibiotics, from wastewater. These systems offer a low-cost, biodegradable, and locally adaptable solution, particularly for developing regions where access to advanced water treatment infrastructure is limited.

Several challenges remain affecting the large-scale implementation of CNF-based water filtration. One of the primary limitations is the scalability of CNF production, as some preparation methods require large energy input or chemical treatments that may not be feasible at an industrial scale [7]. Also, variability in raw material sources can lead to inconsistencies in CNF properties, affecting their performance in filtration applications. The long-term stability, regeneration, and reuse of CNF-based filters also require further research. The mini review aims to provide a comprehensive overview of CNFs as sustainable materials for water filtration applications. It focuses on the sources and preparation methods of CNFs, their structural and functional properties, and the mechanisms involved in pollutant removal.

Preparation of CNFs

CNFs are primarily derived from lignocellulosic biomass, which represents one of the most abundant and renewable natural resources on Earth. Common sources of cellulose include wood, plant fibers, and a wide range of agricultural residues such as banana fibers, rice husk, sugarcane bagasse, and other agro-wastes. These materials are rich in cellulose and offer a sustainable, low-cost feedstock for CNF production. The utilization of agro-waste not only adds value to otherwise discarded biomass but also contributes to waste management and environmental sustainability. Banana fibers have been extensively explored due to their availability and high cellulose content, making them suitable precursors for nanocellulose extraction.

Plant cell walls, composed of cellulose, hemicellulose, and lignin, require pretreatment steps to isolate cellulose fibers before nanofibrillation [8]. These steps include mechanical, chemical, or combined approaches to remove non-cellulosic components and break down the fibrous structure. Mechanical methods such as high-pressure homogenization and grinding can produce CNFs, but these processes are often energy-intensive and may require power input for nanoscale fibrillation.

Chemical methods are widely used to enhance the efficiency of CNF production and reduce energy consumption. Among these, acid hydrolysis is commonly used to remove amorphous regions of cellulose, thereby forming nanoscale fibrillar structures. In addition, alkali treatment and bleaching are essential pretreatment steps that remove lignin, hemicellulose, and impurities, improving the purity and reactivity of cellulose fibers [9]. These treatments convert crystalline regions into nanofibers through controlled hydrolysis.

A major step in CNF preparation is the development of TEMPO-mediated oxidation, which is considered an efficient chemical approach. This method selectively oxidizes the primary hydroxyl groups on cellulose to carboxylate groups under mild aqueous conditions, forming the individual nanofibers with uniform diameters and high aspect ratios [10]. The introduction of surface charges through this process enhances electrostatic repulsion between fibrils, helping with easy dispersion in aqueous media and reducing the need for mechanical processing. Also, the method operates at low energy, making it more sustainable than conventional techniques.

In recent years, combined approaches integrating chemical pretreatment with mild mechanical methods have been increasingly adopted to optimize CNF production. Such strategies reduce energy requirements while maintaining structural integrity and functional properties [11]. The selection of sources and preparation methods plays a critical role in determining the physicochemical characteristics and performance of CNFs in water filtration.

CNFs Property

CNFs, with a combination of structural, chemical, and mechanical properties, are highly suitable for water filtration. Major characteristics of CNFs are their nanoscale dimension, with diameters below 100 nm and high aspect ratios, which contribute to a large specific surface area. This high surface area improves the interaction between CNFs and various pollutants, hence improving adsorption efficiency [12]. CNFs also form highly porous, interconnected network structures, which are advantageous for efficient water flow while filtering contaminants. The surface chemistry of CNFs plays a major role in the filtration performance. Cellulose contains abundant hydroxyl groups, which can be chemically modified to functional groups such as carboxyl and aldehyde [13]. TEMPO-mediated oxidation introduces negatively charged carboxylate groups on the nanofiber surface, increasing their ability to bind positively charged metal ions and other contaminants through electrostatic interactions. This facilitates the formation of stable dispersions and composite materials for advanced filtration systems. CNFs exhibit high strength and flexibility, with tensile strength and elasticity superior to those of other synthetic nanomaterials. These properties help the fabrication of filtration membranes and composite structures that can withstand mechanical stress [14]. Also, CNF-based films and membranes exhibit excellent barrier properties, including low gas and contaminant permeability under controlled conditions. Being prepared from renewable biomass, CNFs are biodegradable, non-toxic, and environmentally friendly compared to many conventional synthetic nanomaterials. This makes them suitable for sustainable water treatment technologies, where minimizing environmental impact is considered [15]. These properties collectively enhance pollutant removal, making CNFs versatile and efficient components in water treatment systems.

Mechanisms of Water Filtration

The high specific surface area and porous network structure of CNFs provide numerous active sites for the binding of contaminants. Pollutants such as heavy metal ions can be adsorbed onto the surface of CNFs through electrostatic interactions and bonding. The presence of hydroxyl and carboxyl functional groups leads to strong interactions with metal ions, thereby improving adsorption efficiency [16]. Surface modification, particularly through oxidation, increases the

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density of negatively charged groups, thereby enhancing the affinity of CNFs for positively charged contaminants.

Electrostatic interactions play a critical role in pollutant removal in aqueous systems containing charged species. CNFs with carboxylate groups exhibit a net negative charge, thereby attracting and binding cationic pollutants such as lead, cadmium, and other heavy metals. This charge-based interaction not only enhances adsorption capacity but also enables selective removal of specific contaminants based on their charge [17]. Also, the formation of stable complexes between CNFs and pollutants further improves retention and prevents re-release into the water system.

Along with adsorption and electrostatic interactions, physical filtration is another important mechanism. CNFs can form dense, interconnected nanofibrous networks that act as filtration membranes. These structures possess nanoscale pores that can trap suspended particles, microorganisms, and larger organic molecules. The high porosity of CNF-based membranes ensures efficient water permeability while maintaining effective filtration. This makes CNFs suitable for membrane-based filtration systems where both flow rate and filtration efficiency are critical.

Chemical interactions, including complexation and redox reactions, also contribute to contaminant removal [18]. Functional groups on CNF surfaces can form complexes with metal ions, stabilizing them and facilitating their removal from aqueous solutions. In some cases, modified CNFs added into composite systems may participate in catalytic or redox processes that degrade organic pollutants into less harmful compounds. CNF-based composite filters combined with clay demonstrated improved adsorption and filtration efficiency due to synergistic interactions between the components. Such systems control both the adsorption capacity of CNFs and the properties of the supporting materials for effective pollutant removal.

Applications for CNFs in Water Filtration

Heavy metals such as lead, cadmium, mercury, and arsenic have severe health and environmental risks due to their toxicity and persistence. CNFs with carboxyl groups exhibit strong adsorption capacity for these metal ions via electrostatic interactions and complexation. The high surface area and abundance of active sites help efficient binding, making CNFs effective adsorbents for heavy metal remediation [19]. Studies have demonstrated that CNF-based materials can achieve high adsorption capacities, offering a sustainable alternative to these adsorbents.

CNFs have shown potential for eliminating organic pollutants such as dyes, pesticides, and industrial chemicals. These pollutants are often resistant to traditional treatment methods and can persist in the environment, causing long-term ecological damage [20]. CNFs can absorb organic molecules through a combination of physical and chemical interactions, by hydrogen bonding and van der Waals forces. Also, modified CNF-based composites improve the degradation or immobilization of such pollutants, improving treatment efficiency.

Another important application of CNFs is in the removal of microbial contaminants. The porous network structure of CNF-based membranes enables the physical trapping of bacteria and other microorganisms, contributing to water disinfection [21]. CNFs can be added with antimicrobial agents to improve their ability to inhibit microbial growth. This dual functionality makes CNFs suitable for water filtration systems, particularly in regions with limited access to clean water.

Antibiotics are commonly detected in wastewater due to their widespread use and incomplete metabolism in humans and animals. CNF-based filtration systems have proved potential in removing these contaminants through adsorption and filtration mechanisms. Composite filters containing CNFs and locally available materials, such as clay, have been developed as cost-effective solutions for antibiotic removal. These systems have demonstrated high efficiency in reducing antibiotic concentrations, thereby increasing their applicability for sustainable wastewater treatment.

Electrospun CNF-based membranes exhibit high porosity, uniform pore distribution, and excellent mechanical stability, making them suitable for a wide range of filtration applications. The addition of CNFs into polymer matrices or hybrid composites enhances the mechanical strength, adsorption capacity, and durability of filtration systems.

Challenges and Limitations

Several challenges restrict the widespread application of CNFs in water filtration technology [22]. One of the primary limitations is the scalability of CNF production. While laboratory-scale methods such as TEMPO-mediated oxidation and acid hydrolysis have proved efficient, scaling these processes to industrial levels remains challenging due to high costs, energy requirements, and process complexity. Another limitation is the variability in raw material sources. CNFs derived from different biomass sources show variations in structural and chemical properties, which influence their performance in filtration applications. The long-term stability and durability of CNF-based filtration systems also require further research. Long-term exposure to aqueous environments may cause CNFs to undergo structural degradation or loss of functional groups, potentially reducing their filtration efficiency.

Future Perspectives

The future development of CNF-based water filtration technology is expected to focus on improving functionality, scalability, and applicability [23]. One of the major areas of research is improving surface functionalization techniques to enhance the selectivity and efficiency of pollutant removal. Introducing specific functional groups or incorporating catalytic components can help CNFs target a broader range of contaminants, including emerging pollutants such as pharmaceuticals and endocrine-disrupting compounds. Another important area is the addition of CNFs with other materials to form hybrid nanocomposites. Combining CNFs with inorganic materials, polymers, or naturally occurring substances such as clay can significantly enhance mechanical strength, adsorption capacity, and durability. Future research should also focus on improving the stability and reusability of CNF-based filtration systems. Developing regeneration techniques and enhancing the structural integrity of CNF membranes will be essential for long-term application.

Conclusion

CNFs have emerged as highly promising materials for sustainable water filtration due to their unique combination of structural, chemical, and environmental properties. CNFs offer advantages over traditional materials, including biodegradability, high surface area, and the ability to undergo surface modification for enhanced pollutant removal. Their effectiveness in removing a wide range of contaminants,

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including heavy metals, organic pollutants, and pharmaceutical residues, demonstrates their versatility and potential to address global water pollution challenges. The integration of CNFs into composite systems further enhances their performance, enabling the development of cost-effective and efficient filtration technologies suitable for diverse environmental conditions. However, challenges related to production scalability, material variability, and long-term stability must be solved to enable their widespread adoption. Continued research focused on improving synthesis methods, enhancing material performance, and understanding environmental impacts will be essential to advancing CNF-based technologies.

Disclosure Statement

No potential conflict of interest was reported by the author.

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