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EXPLORING CELLULOSE AND NANOCELLULOSE BASED MATERIALS FOR WATER PURIFICATION: A MINI REVIEW

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ABSTRACT: Cellulose and nanocellulose-based materials have emerged as promising candidates for water purification due to their abundance, biodegradability, and tunable properties. This review examines several materials made from cellulose, such as hydrogels, composites, and nanofibers, emphasizing their special functionalization techniques and structural characteristics that improve adsorption and filtering properties. We compare their performance indicators with traditional purification techniques to assess how effectively they remove contaminants such as heavy metals, organic pollutants, and infectious substances. Cellulose exhibits stiffness and a crystalline structure due to hydrogen bonding. Its basic state is compact, porous, and rich in binding sites, making it effective as a bio adsorbent. Cellulose modification techniques are divided into two categories: direct modifications (e.g., sulfation, etherification, and esterification) and polymerization methods (e.g., free radical, ring-opening) that graft monomers onto cellulose. The review also discusses issues with cellulose-based adsorbents' scalability, affordability, and regeneration. Nanocellulose has demonstrated significant effectiveness in water purification, with various modification techniques enhancing its performance. Nanocellulose, with its enhanced mechanical properties and unique nanoscale features, offers significant advantages over traditional cellulose, making it a promising material for a wide range of advanced applications particularly in water purification. Previous studies indicate that the preparation of composites from nanocellulose has yielded promising results in the treatment of contaminated water. The potential relevance of cellulose materials in sustainable water management practices is emphasized by discussing future perspectives on inventive fabrication techniques and their integration into current water treatment systems.

Keywords: water purification, cellulose, nanocellulose

1. INTRODUCTION

Water treatment is becoming a major global concern with the increasing need for safe and clean water (Werber *et al*., 2016). Novel materials and technologies are essential to solve the urgent problems of rising pollution, contamination, and resource scarcity (Coccia & Bontempi, 2023). Traditional water treatment methods to ensure safety and purification of water for various applications are coagulation (Kolya & Tripathy, 2013), filtration (Schelling *et al*., 2023), disinfection, adsorption (Ghorai *et al*., 2014), and membrane filtration. Traditional methods have their own set of strengths and limitations. Consequently, the development of contemporary water treatment methods has been greatly aided by the advancement of adsorption and membrane filtering technologies, guaranteeing the availability of safe and clean drinking water to populations across the globe. Polymers are crucial to the adsorption and membrane filtration processes of water treatment, as they improve performance. However, interest in bio-polymer-based adsorbents and membranes has increased due to issues regarding the biodegradability of synthetic polymers. Since bio-polymer-based adsorbents and membranes are environmentally friendly, they present an alluring substitute (Kolya, 2023). Additionally, bio polymeric nanocomposite materials have lately caught the interest of researchers, as they show promise for a variety of water treatment applications (Arif *et al*., 2019). These materials offer improved performance and efficiency by combining the benefits of biopolymers made from renewable resources with the special qualities of nanofillers. Since biopolymers are biocompatible, biodegradable, and versatile, they have various benefits in the water treatment industry (Romero-montero *et al*., 2023). This review explores the use of cellulose and nanocellulose, in water purification, along with their various modifications.

2. LITERATURE REVIEW

Cellulose

Cellulose is considered the highest abundant polymer on earth which compromises around 40-50% of the biomass (Abdelhamid, 2024). The 1,4 glucoside linkages bind the –D-glucopyranose residues that make up cellulose, a linear biopolymer (Al-Gethami *et al*., 2024). Numerous functional groups, including hydroxyl groups, are present in cellulose and help contribute to its hydrophilic properties (Sharma, 2023). The functional groups on the surface of cellulose allow for the attachment of a variety of molecules (Lin *et al*., 2012). Three hydroxyl groups (-OH) are found in cellulose units, which are anhydroglucose molecules, at carbons 2, 3, and 6. These hydroxyl groups provide the material with its stiffness and crystalline structure by forming intra- and intermolecular hydrogen bonds both inside and between the macromolecules. It must be at its most basic state, which is compact, porous, and rich in active binding sites for cellulose to function as a bio-adsorbent (Jyoti *et al*., 2022). Cellulose modification techniques are primarily categorized into two main types. The first category involves direct modification methods, where functional groups such as sulfation (Rizkyana *et al*., 2022), etherification (Ranjha *et al*., 2023), carbanilation (Barthel & Heinze, 2006), silylation (Gupta *et al*., 2023), esterification (Tang *et al*., 2016), and amination (Azzam *et al*., 2015) are attached directly to the hydroxyl groups of cellulose molecules.

The second category encompasses techniques such as free radical polymerization, ring-opening polymerization, and controlled radical polymerizations, which graft monomers onto cellulose chains either in homogeneous or heterogeneous solutions (Dalej *et al*., 2022). These modified cellulose components play a crucial role in water purification and the removal of hazardous organic and metal contaminants (Sari *et al*., 2023). Heavy metal ion adsorption on cellulose adsorbents can be facilitated through ion-exchange processes, where heavy metal ions are swapped with non-toxic ions like sodium (Na^+) or potassium (K^+). This method is specifically used for removing metal ions (Al-Gethami *et al*., 2024). The materials can also be processed using them to create hydrogels and aerogels. The three-dimensional network materials known as hydrogels are composed of chains of polymers joined by physical or chemical interactions (Khan *et al*., 2023). Chemical modifications such as crosslinking and grafting or physical (such as blending, inclusion, and filler addition) techniques can be used to modify cellulose hydrogels (Radoor *et al*., 2024). The degree of cross-linking and the concentration of the polymers determine the mesh size, or precise size of the holes within each hydrogel (Khan *et al*., 2023).

Hydrogels based on cellulose have been successfully developed to remove hazardous dyes, heavy metals, and other environmental contaminants (Radoor *et al*., 2024). As amine groups are added, polyethyleneimine chemically bonds to oxidized cellulose hydrogels to improve their adsorption capabilities. Furthermore, adding 2-acrylamido-2-methylpropane sulfonic acid (AMPS), which creates sulfonic acid groups, to cellulose-based hydrogels improves their capacity to absorb cationic dyes and metal cations (Zhang *et al*., 2023). The polymer chain's abundance of hydroxyl groups, which easily form hydrogen bonds, makes processing challenging and restricts the wider application of cellulose-based hydrogels. Additionally, the poor mechanical qualities and limited biocompatibility of these hydrogels limit their usefulness and recyclability in adsorption applications (Zhang *et al*., 2023). Cellulose fibers must be altered to incorporate both positive and negative charges. Nucleus addition, affinity procedures, and electrophilic addition are some of the techniques used to accomplish this (Abdelhamid, 2024). Cellulose has a highly ordered and crystalline structure due to its strong hydrogen bonding, which renders it nearly insoluble in typical solvents. The potential applications of cellulose are limited by this attribute particularly those requiring its transformation into soluble or highly processable forms (Ai *et al*., 2021).

Nanocellulose

Nanocellulose (NC) are cellulose that can be produced at nanoscale. Researchers explore nanocellulose due to its favorable physical and chemical properties. These include its natural availability, high strength, rigidity, renewable nature, ability to break down biologically, compatibility with living systems, and overall sustainability (Ma et *al*., 2011). There are range of forms, including TEMPO-oxidized cellulose nanofibrils (TOCNF), bacterial nanocellulose (BNC), cellulose nanocrystals (CNC), enzymatically derived nanocellulose (ENC), and cellulose nanofibrils (CNF) (Sultan *et al*., 2018).

The process of obtaining nanocellulose involves three main steps; pretreatment, removal of color and impurities through bleaching, and separation of the cellulose into nanoscale, respectively (Jali *et al*., 2024). Breaking down cellulose to the nanoscale solves important problems related to layered architectures and improves the antifouling capabilities of CNC membranes. Using CNCs, Huang et al. improved the water permeability and chlorine resistance of thin film composite nanofiltration membranes (Huang *et al*., 2019). The addition of CNCs to thin film composite (TFC) membranes resulted in a significant improvement in salt rejection showing 96.1% of $MgSO_4$ and 98.3% of Na_2SO_4 removal. Moreover, the water flux increased dramatically to 106.9 L m^{-2} h^{-1} as compared to TFC membranes without CNCs. In order to improve antifouling and separation efficiency, Bai et al. added cellulose nanocrystals to a polyamide (PA) layer while creating a thin film composite (TFC) membrane (Bai *et al*., 2018). The resulting CNC-TFC membranes showed a 60.0% improvement in permeability compared to TFC membranes without CNCs, with just 0.02 w/w % of CNCs. CNC-TFC membranes exhibit greater fouling resistance and recovery capabilities compared to conventional membranes, making them attractive options for desalination and water purification applications. Among various functionalization techniques, the carboxylation of nanocellulose for the uptake of cationic species has been the most extensively researched (Hasani *et al*., 2008). This approach offers the highest adsorption efficiency for a wide range of metallic cations and cationic dyes. Additionally, esterification with dicarboxylic acids or oxidation mediated by TEMPO can enhance the sorption of cationic species (Hasani *et al*., 2008).

The carboxylated CNCs produced using the TEMPO-oxidation method exhibited significantly better adsorption of methylene blue (769 mg/g at pH 9) compared to the sulfated CNCs, which only absorbed 118 mg/g at the same pH level (Batmaz *et al*., 2014). Carboxylated CNCs can alternatively be synthesized by esterifying surface hydroxyl groups with maleic anhydride. This method enhances the adsorption efficiency for various cationic dyes, including crystal violet, methylene blue, and malachite green. For instance, at pH 4, the maximum adsorption of crystal violet reached 244 mg/g (Qiao *et al*., 2015). When polymers with amino groups were grafted onto nanocellulose, they exhibited a markedly increased adsorption rate for various dyes. This improvement is attributed to the interactions between the dyes and the amino groups, especially the anionic dyes (Jin *et al*., 2015). In one approach to produce cationic CNCs, sodium periodate is used for oxidation, followed by a reaction with ethylenediamine. CNCs prepared using this method showed a maximum adsorption capacity of 556 mg/g for acid red GR dye. The adsorption performance of these cationic CNCs was affected by the pH-dependent behavior of the functional groups. Unlike CNCs with carboxyl groups, the amine groups in these cationic CNCs demonstrated peak adsorption at lower pH levels, with a decline in uptake capacity as the pH increased (Jin *et al*., 2015). When the cationic CNFs were produced through quaternization with glycidyltrimethyl ammonium chloride, it was found that the uptake capacity for Congo red was 664 mg/g and acid green 25 was 683 mg/g within a few seconds (Pei *et al*., 2013).

3. CONCLUSION

Due to their special structural qualities and adaptability, cellulose and its derivatives, including nanocellulose, have shown a great deal of promise in water purification applications. By employing diverse modification techniques, such as carboxylation and esterification, or sophisticated polymer grafting methods, these materials can be precisely tailored to improve their adsorption capabilities for pollutants like organic dyes and heavy metals. The continuous development of cellulose-based adsorbents reflects our increasing knowledge of their versatility and effectiveness in solving challenging problems related to water contamination. Further research and development into cellulose modifications will result in even more sustainable and effective water treatment technologies, highlighting the critical role that these biopolymers play in pollution control and environmental management.

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