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Published in:
Journal of Bioresources and Bioproducts

DOI:
10.1016/j.jobab.2023.12.002

First published: 10/12/2023

Document Version
Version created as part of publication process; publisher's layout; not normally made publicly available

Link to publication

Citation for pulished version (APA):
Mishra, K., Siwal, S. S., Sithole, T., Singh, N., Hart, P., & Thakur, V. K. (2023). Biorenewable materials for water remediation: The central role of cellulose in achieving sustainability. *Journal of Bioresources and Bioproducts*. Advance online publication. https://doi.org/10.1016/j.jobab.2023.12.002

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Journal of Bioresources and Bioproducts xxx (xxxx) xxx

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Journal of Bioresources and Bioproducts

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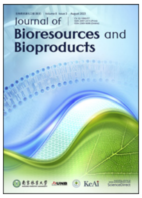

Review

Biorenewable materials for water remediation: The central role of cellulose in achieving sustainability

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ARTICLE INFO

Keywords:
Cellulose
Wastewater treatment
Hydrogel
Nanocrystal
Cellulose membrane

ABSTRACT

As the population increases and manufacturing grows, greenhouse gas and other harmful emissions increase. Contaminated with chemicals such as dyes, pesticides, pharmaceuticals, oil, heavy metals or radionuclides, wastewater purification has become an urgent issue. Various technologies exist that can remove these contaminants from wastewater sources, but they often demand high energy and/or high cost, and in some cases produce contaminant laden sludge that requires safe disposal. The need for methods which are less capital intensive, less operationally costly and more environmentally friendly is suggested. Cellulose-based materials have emerged as promising candidates for wastewater treatment due to their renewability, low cost, biodegradability, hydrophilicity, and antimicrobial property. In this review article, we focussed on developing sustainable and biodegradable cellulose-based materials for wastewater treatment. This article deals with cellulose-based materials' scope and their conversion into valuable products like hydrogel, aerogel, cellulose composites, and nanocellulose. The cellulose-based materials have no harmful environmental impact and are plentiful. The modified cellulose-based materials applying as membrane, adsorbent, sorbent, and beads to purify the wastewater were discussed. Finally, the challenges and future prospects of cellulose-based materials for wastewater treatment were considered, emphasizing their potential to be sustainable and eco-friendly alternatives to traditional materials used in wastewater treatment.

Introduction

Water pollution is a major environmental challenge threatening public health and ecosystem sustainability. Wastewater treatment is essential for removing contaminants from water before it is released into the environment (Hernández-Delgado, 2015; Brooks et al., 2016). Traditional materials used in wastewater treatment, such as activated carbon and metal oxides, have several limitations, including high cost, limited availability, and environmental concerns (Sheoran et al., 2022; Siwal et al., 2022c; Kaur et al., 2023a). Cellulose, the most abundant natural polymer, is a promising alternative for wastewater treatment applications due to its renewability, sustainability, biodegradability, and low cost (Sanyang et al., 2016; Tu et al., 2021). In recent years, significant progress has been made in the synthesis, processing, and applications of cellulose-based materials for wastewater treatment (da Silva et al., 2023;

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https://doi.org/10.1016/j.jobab.2023.12.002

Available online xxx
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Please cite this article as: K. Mishra, S.S. Siwal, T. Sithole et al., Biorenewable materials for water remediation: The central role of cellulose in achieving sustainability, Journal of Bioresources and Bioproducts, https://doi.org/10.1016/j.jobab.2023.12.002

Motloung et al., 2023; Nawaz et al., 2023). After cellulose, lignin is the second most abundant natural biopolymer and is used in various applications like paper making and the production of ethanol (Thakur et al., 2014).

From ancient times, the human being was highly dependent on hydrocarbon fuel resources. These non-renewable resources by definition deplete over time, and their use leads to serious environmental concerns like global warming and depletion of the ozone layer. Much interest has been taken in developing sustainable biomass to overcome this situation, mainly made up of lignin, cellulose, and hemicellulose (Mussatto and Dragone, 2016; Eqbalpour et al., 2023; Sigmond et al., 2023). Cellulose-based materials are readily available and are biodegradable, renewable, and economical-friendly. Cellulose is converted into water-soluble materials like cellulose acetate (hydroxypropyl) and methylcellulose. Cellulose consists of 1 000−15 000 glucose (β) units arranged linearly in a chain to form a polymer. Cellulose is a semi-rigid polymer having 150 MPa strength (Wang et al., 2012; Bin Bakri and Rahman, 2022; Rana et al., 2023b). The nano-constituents in cellulose can be extracted using mechanical and chemical methods. New forms of cellulose, like cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs), can be extracted by the development of nanotechnology. By the breakdown of amorphous domains, rod-shaped CNCs are formed. CNFs comprise side-by-side amorphous and crystalline parts of cellulose and are flexible, long, and thin. Nowadays, nanocellulose is an active candidate/field for study within material science (Habibi, 2014; Shen et al., 2020).

Microorganisms also produce cellulose, which is extracellular and known as bacterial cellulose. In addition to starch, alginate, xylenes, chitosan, and silk fibroin, this bacterial cellulose can be used to form biocomposites. In addition, bacterial cellulose is also utilized in bioelectronics and biomedicine (Li et al., 2018b). These cellulose-based materials can also be used in various applications like treating wastewater, catalysis, energy storage, pharmaceuticals, etc. For water treatment, cellulose-based materials are utilized as flocculants, adsorbents, and in oil-water separating membranes. Further, it was found that cellulose fibres obtained from *Canna indica* waste, could be used to treat domestic wastewater after valorisation (Sharma et al., 2023). Pine needle based cellulose materials were reported in wastewater treatment as well (Rana et al., 2023a). Further, various cellulose-based materials are used for the removal of heavy metal by adsorption, for example sugarcane bagasse for removal of Cu(II), Cu(IV) and Hg ions from wastewater (Karnitz et al., 2007), wood sawdust to remove Cd(II) ion, and sugarcane bagasse and coconut tree sawdust to remove Zn(II), Pb(II), and Cu(II) from polluted water (Pranata Putra et al., 2014). These examples show the sustainability and opportunity of cellulose-based materials in wastewater treatment. This review focuses on converting cellulose into valuable products for wastewater treatment. Furthermore, the challenges of cellulose-based materials' utilization in various applications were discussed. Traditional wastewater treatment methods often rely on energy-intensive processes and generate large amounts of sludge and chemical waste. There is an increasing interest in developing sustainable and efficient materials for wastewater treatment to address these concerns. This article explores the scope of cellulose-based sustainable materials, highlighting their processing techniques and various applications in wastewater treatment.

Scope of cellulose-based materials

Cellulose is a versatile natural polymer with a wide range of properties and applications. The use of cellulose-based materials has been explored in fields including biomedical, energy, packaging, and environmental applications (Shao et al., 2023; Won et al., 2023).

In wastewater treatment, cellulose-based materials have shown great potential as sustainable and eco-friendly alternatives to traditional materials. The scope of cellulose-based materials for wastewater treatment includes developing novel materials, modifying existing materials, and integrating them with other technologies to enhance their performance. Cellulose-based materials can be used as adsorbents, membranes, and catalysts to remove various pollutants from wastewater, including heavy metals, organic compounds, and dyes (Liu et al., 2020; Sayyed et al., 2021). The scope of cellulose-based materials for wastewater treatment also includes their use in decentralized wastewater treatment systems, where low-cost and efficient materials are required. Cellulose-based materials can be produced from various natural and renewable sources, such as agricultural waste, wood, and bacterial cellulose, which highlights their potential within sustainable and circular economy applications (Ribul et al., 2021; Siwal et al., 2021a; Mujtaba et al., 2023).

Various sources provide energy, like solar, wind, hydrothermal, and fuel cells in daily life (Kasaeian et al., 2023; Lee et al., 2023). However, the main problem associated with these sources is the high cost of equipment and catalysts (Armor, 1999; Etim et al., 2020; Mishra et al., 2023b). Cellulose is inexpensive and has low lifetime carbon emissions, hence, they are widely used in the economic treatment of wastewater (Sheoran et al., 2022, 2023). Cellulose-based materials are naturally available and can remove both inorganic and organic pollutants from wastewater using methods such as chemical precipitation, ultrafiltration, evaporation, and adsorption (Peng et al., 2020; Siwal et al., 2022a).

Research shows that approximately 10 000 t cellulose can be obtained per year from plant stalks, straw, shells, plant fibres, grasses, etc. (Azizi Samir et al., 2005). The primary cellulose sources are bacteria, algae, wood, tunicates, plants, etc. (Moon et al., 2011). Cellulose is a polymer in which glucose is the monomer attached by 1,4 β-linkage. Due to some functional groups like carboxylic acid and hydroxyl, cellulose can combine with some organic species. These organic species provide extra active groups that make cellulose suitable for diverse applications. These functionalized groups help the modification of cellulose into nanoparticles (NPs) with metal-organic frameworks (MOFs), graphene oxide (GO), Ag NPs etc. (Liao et al., 2018; Askari et al., 2022). Cellulose-based materials for water treatment are popular due to their chemical inertness, rich surface chemistry, and large surface area. Due to these properties, nanocellulose is particularly suitable for making filters and membranes that exhibit good ability to remove pollutants from contaminated water (Voisin et al., 2017). For the treatment of drinking water, nanofiltration membranes are very suitable. Cellulose-based membranes are often selected due to their relatively low cost, biodegradability, and energy saving compared to petrochemical-based membranes (Li et al., 2022). For water treatment, coagulation or flocculation is widely used, in which coagulants (chemicals) are added to polluted water to cause neutralization of charged particles present in water. Neutralized particle aggregation occurs followed by precipitation of impurities. Coagulation processes driven by chemical additives produce large amounts of alkaline sludge and create secondary pollutants. To overcome this situation, cellulose can be used as an eco-friendly coagulant alternative (Abdelhamid and Mathew, 2021a). To adsorb the metal ions in contaminated water, functional groups in cellulose play a significant role. Further, to enhance the rate of adsorption, cellulose materials are modified by amination (Araki et al., 2001), sulphonation (Septevani et al., 2020), phosphorylation, xanthation (Pillai et al., 2013), and thiols (Choi et al., 2020). These modifications also strengthen the bond between metal ions and adsorbents. Ongoing research and developments in the field of cellulose-based materials for wastewater treatment are expected to yield new and innovative solutions for addressing water pollution challenges.

Processing of cellulose-based materials into valuable products

Processing methods vary depending on the specific cellulose-based material, the desired products, and the planned applications. Investigators and enterprises are actively developing novel processing approaches seeking to improve the value and versatility of cellulose-based materials, widening their utilization in different sectors. Natural polymers like cellulose have many applications within textiles, fuel, catalysis, paper, and pharmaceuticals (Mülhaupt, 2013; Nasrollahzadeh et al., 2021). Research has uncovered opportunities for the conversion of these polymers into novel nanomaterials, such as CNCs and CNFs, which show excellent and unique characteristics superior to other cellulose. For instance, cellulose's surface area increases from 4 to 500 m^2/g by converting it into nano papers using a mechanical approach (Banavath et al., 2011). In water treatment removing pollutants like heavy metals, organic materials, and pharmaceutical waste are critical steps to make it suitable for drinking or other agricultural use (Wang, 2019). Nanocellulose has a large surface area and high strength, making it particularly suitable for selectively permeable membranes and water purification filters. Cellulose-based material can also be converted into other valuable products such as hydrogels, aerogels, nanocomposites, and membranes.

Aerogels

Cellulose-based aerogel is a solid porous material. Kistler (1931; 1932) synthesized aerogels for the first time in 1930 by eliminating liquid in a wet gel via supercritical drying. Preparation of cellulose aerogel requires three steps: dissolving cellulose or a derivative of cellulose, formation of cellulose gel via means of the sol-gel procedure, and drying cellulose gel to retain its 3D assembly (Long et al., 2018). The cellulose aerogel preparation process with their further modification is shown in Fig. 1.

Cellulose aerogels have more compressive strength and superior biodegradability than silica and synthetic polymer-based aerogels. Cellulose aerogel has excellent performance as a separator of oil/water and carrier of metal nanoparticles in adsorption, heat insulation, etc. Depending on the source, cellulose aerogels are classified into three classes: natural cellulose aerogels (including nanocellulose aerogels and bacterial cellulose aerogels), renewed cellulose aerogels, and cellulose derivative aerogels. The properties of these different kinds of cellulose aerogel are listed in Table 1.

Hydrogel

Hydrogels (HGs) are made of a natural or synthetic substance arranged in a three-dimensional network with considerable flexibility. HGs can also retain much water and have a soft rubber-like structure. These properties lead to their use in many applications (Siwal et al., 2022b). The substantial part of HGs is a cross-linked network of various polymeric chains, with the appearance of a three-dimensional mesh as shown in Fig. 2. The empty spaces are filled with water or any other fluid (Ullah et al., 2015).

Cellulose contains many –OH groups that provide useful structures and characteristics. By physical crosslinking in the cellulose solution, cellulose-based hydrogels (CBHs) can be synthesized. Some of the derivatives of cellulose that are water soluble are used in various forms like emulsifiers, surfactants, binding agents, food additives etc., as they are biocompatible. Some specific derivatives of cellulose like hydroxypropyl cellulose (HPC), methylcellulose (MC), hydroxypropyl methylcellulose (HPMC), and carboxymethyl cellulose (CMC) are utilized for HGs synthesis via physical and chemical crosslinking. Physical crosslinked HGs contain electrostatic interaction, H-bonding, and associative polymer-polymer interaction, however, it will break in chemical crosslinking formation and covalent bonds. (Chang and Zhang, 2011).

The CBHs are very popular in removing dyes, heavy metals from contaminated water via adsorption. They are soluble in organic solvents, biodegradable, abundant, cheap, and have a high surface area and adsorption capacity, etc. CBHs can be recycled after use. Their hydrophilic ability makes them a conspicuous candidate for wastewater treatment (Akter et al., 2021). CBHs can be shaped into various physical structures like beads, spheres, blocks, cylinders, nano, microparticles and thin films using different synthesis processes. Multiple approaches to CBH synthesis are shown in Fig. 3.

The CBHs remove pollutants in wastewater, such as heavy metals, dye, and oil. Part of the CBH applications are listed in Table 2. Some CBHs lose their pollutant adsorption ability after regeneration. To investigate this issue, some researchers concluded that regeneration power is regained when the renewal is done in NaOH (Satari et al., 2019). CBHs can be modified by chemical and physical reactions to adjust or increase their adsorption ability. The study of the composition and structure of CBHs shows that they have a positive effect on wastewater treatment (Pathak and Navneet, 2017).

Other cellulose composite

Cellulose and chitosan-based composites in membrane-based techniques have achieved much attention (Thakur and Voicu, 2016). In some cases, cellulose is used as an adsorbent when modified with sodium montmorillonite (NaMMT) and acts as a composite

Table 1
Properties of different kinds of cellulose aerogel.

Material	Drying method	Porosity (%)	Density (g/cm^3)	Specific surface area (m^2/g)	Reference
Natural cellulose aerogel					
Nano-fibrillated cellulose, SiO_2	Freeze-dried	85.15–96.46	0.055–0.295	11.3 – 700.1	Fu et al., 2016
CNC, SiO_2	Ambient pressure drying	–	0.137–0.151	620–688	Li et al., 2017
CNC	Supercritical CO_2 dried	91–95	0.078–0.155	216–605	Heath and Thielemans, 2010
BC	Supercritical CO_2 dried	–	0.008	200	Liebner et al., 2010
BC, Silica	Freeze-dried	89–99.6	0.007–0.229	129–541.1	Sai et al., 2014
BC, GO	Freeze-dried	99.84–99.92	–	–	Wang et al., 2014
Regenerated cellulose aerogel					
Cellulose fibres	Freeze-dried or Supercritical CO_2 dried	–	0.01–0.06	80–250	Hoepfner et al., 2008
Cellulose powder	Supercritical CO_2 dried	91–99	0.009–0.137	120–230	Karadagli et al., 2015
Cotton linter	Supercritical CO_2 dried	95.5 – 98.1	0.03–0.067	190–328	Pircher et al., 2016
Microcrystalline cellulose	Supercritical CO_2 dried	91–96	0.06–0.3	200–300	Gavillon and Budtova, 2008
Bagasse	Freeze-dried	84.4 – 94.2	0.088–0.236	119–185	Chen et al., 2016b
Waste newspaper	Freeze-dried	98.2 – 98.9	0.017–0.029	296–412	Fan et al., 2017
Paper pulp	Supercritical CO_2 dried	95	0.12–0.17	363–406	Cai et al., 2009
Cellulose derivative aerogel					
Tri acetyl cellulose	Supercritical CO_2 dried	96.1 – 99.6	0.005–0.05	229–958	Fang et al., 2016
Carboxymethylcellulose/CNF	Freeze-dried	93.19–96.84	0.05–0.109	–	Chen et al., 2016a
2,2,6,6-tetramethylpiperidine-1-oxyl; (TEMPO)-CNF	Freeze-dried	98.8 – 99.5	0.008–0.187	12.72–117.8	Jiang and Hsieh, 2014
Hydrophobic CNF	Freeze-dried	98.5	0.023 2	18.4	Mulyadi et al., 2016
CNF-MA	Freeze-dried	–	0.011 2 – 0.031 5	19.5	Kim et al., 2015

Notes: CNC, cellulose nanocrystal; BC, bacterial cellulose; GO, graphene oxide; CNF, cellulose nanofibril; TEMPO, 2,2,6,6-tetramethylpiperidine-1-oxylradical; MA, maleic acid.

Table 2
Applications of cellulose-based hydrogel for removal of pollutants.

Cellulose-based hydrogel	Type of pollutant removed	Synthesis process	Working mechanism	Reference
Carboxymethyl cellulose HG beads	Cu(II), Ni(II), and Pb(II)	Inverse suspension crosslinking	Electrostatic and coordination interactions	Yang et al., 2011
Cellulose-graft-acrylic acid HGs	Cd(II), Ni(II), and Pb(II)	Grifting reaction mechanism	Electrostatic connections and ion exchange	Zhou et al., 2012b
Chitin/cellulose composite HGs	Hg(II), Pb(II), and Cu(II)	Freezing/thawing	Electrostatic and coordination interactions	Tang et al., 2011
Carboxymethyl chitosan/poly (acrylonitrile) HGs	Cu(II), Cd(II), and Co(II)	Crosslinking	Electrostatic interaction	Mohamed et al., 2012
CMC/2-acrylamido-2-methyl propane sulfonic acid HGs	Co(II), Cu(II), Mn(II), and Fe(III)	Copolymerization and crosslinking	Electrostatic and chelating interactions	El-Hag Ali, 2012
TEMPO-oxidized cellulose HGs	Zn(II), Fe(III), Cd(II), and Cs(I)	Nitroxy radical catalysed oxidation	Electrostatic interactions and ion exchange	Isobe et al., 2013
Sugar cane bagasse cellulose and gelatin-based composite HGs	Cu(II)	Crosslinking	Electrostatic and coordination interactions	Maity and Ray, 2017
Cellulose-porous bentonite composite	Azo dye	Crosslinking	Electrostatic interaction	Santoso et al., 2019
Cellulose-based bio-adsorbent	Acid blue, methylene blue dye	Graft copolymerization	Electrostatic interactions and H-bonding	Liu et al., 2015
Chitogen/cellulose HGs	Congo red dye	Freeze-dried	Electrostatic and coordination interactions	Tu et al., 2017
CMC-acrylic acid adsorbent	Methyl orange, disperse blue 2BLN, and malachite green chloride	Graft polymerization	Electrostatic interactions	Zhang et al., 2014a
Carboxymethyl cellulose structured nano-adsorbent	Methyl violet	Sol-gel method	Electrostatic and π-π interactions	Sharma et al., 2020
Lignocellulose-g-poly(acrylic acid)/montmorillonite 3D crosslinked polymeric network HGs	Methylene blue dye	Copolymerization	Electrostatic interactions	Shi et al., 2013
Nanocomposite HG	Crystal violet	Graft polymerization	Electrostatic interactions and H-bonding	Mahdavinia et al., 2013
Super adsorbent cellulose-graft-acrylic acid	Methylene blue dye	Free-radical polymerization	Electrostatic interactions	Zhou et al., 2012b

Notes: HGs, hydrogels; CMC, carboxymethyl cellulose.

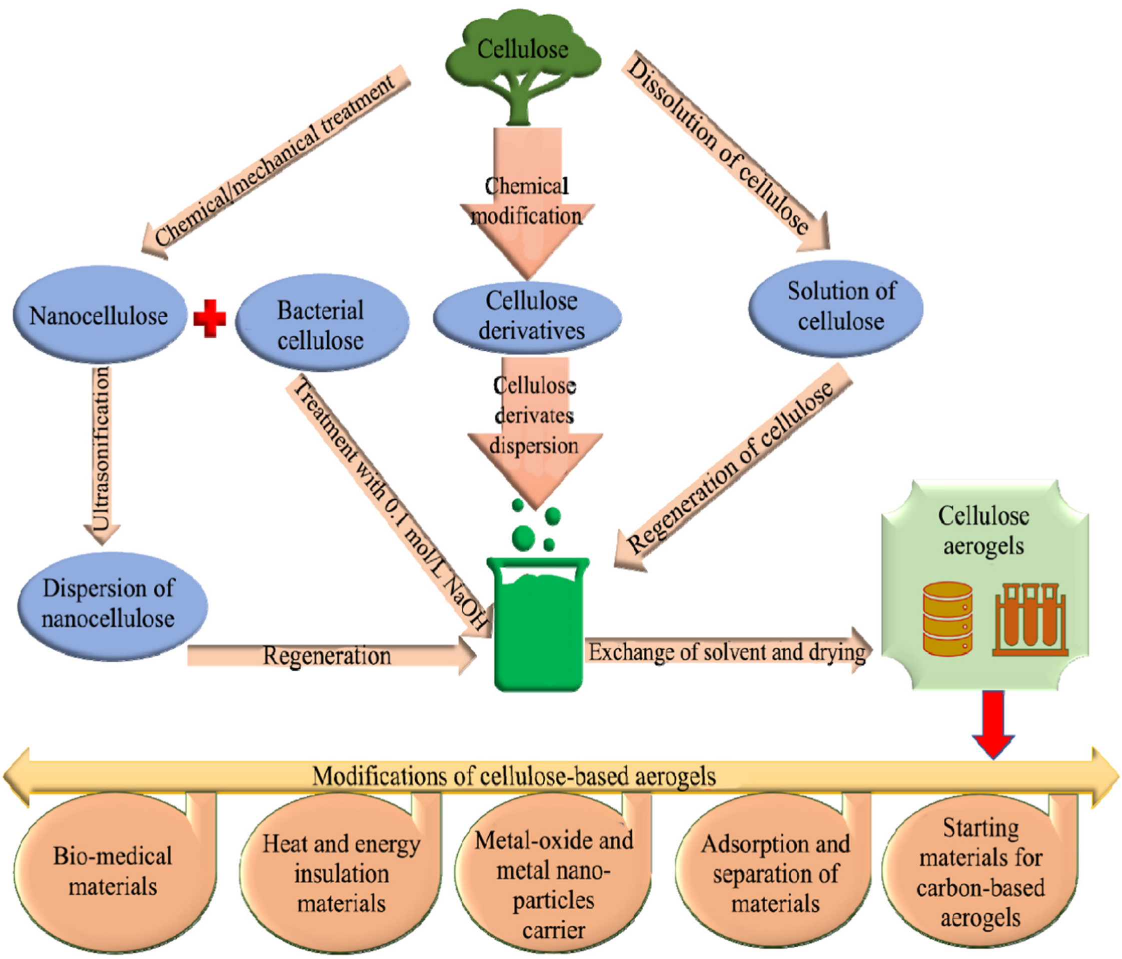


Fig. 1. Fabrication process of cellulose aerogels with their further modifications.

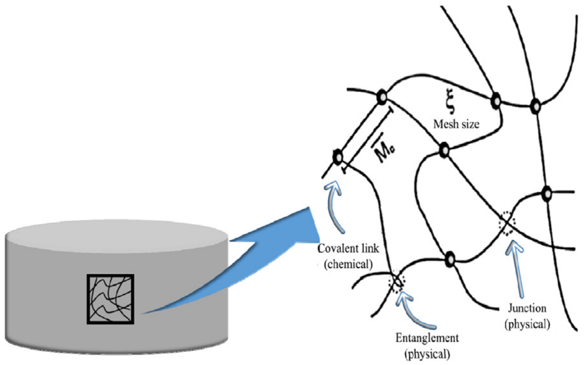


Fig. 2. The structural arrangement of hydrogel (Ullah et al., 2015).

material. NaMMT-modified cellulose composite could be used to eliminate Cr(VI) from aqueous media and be regenerated up to 10 times by using NaOH (Kumar et al., 2012). Chitosan-based cellulose composites can also be fabricated by mixing cellulose with chitosan and used to remove heavy metals from wastewater (Wu et al., 2010; Zhang et al., 2013).

Sun et al. (2009) synthesized a composite to adsorb Cu(II), Pb(II), Ni(II), and Cr (VI) by combining cellulose with chitin using ionic liquids that are eco-friendly. Various materials are used to provide robust capability in the adsorbent when removing heavy metals from polluted water. These materials accelerate the adsorption compared to cellulose. Li et al. (2015) fabricated a nanocomposite by mixing TiO_2 with cellulose fibres (CF), i.e., CF/TiO_2 nanocomposite. The CF/TiO_2 nanocomposite exhibited good efficiency for the

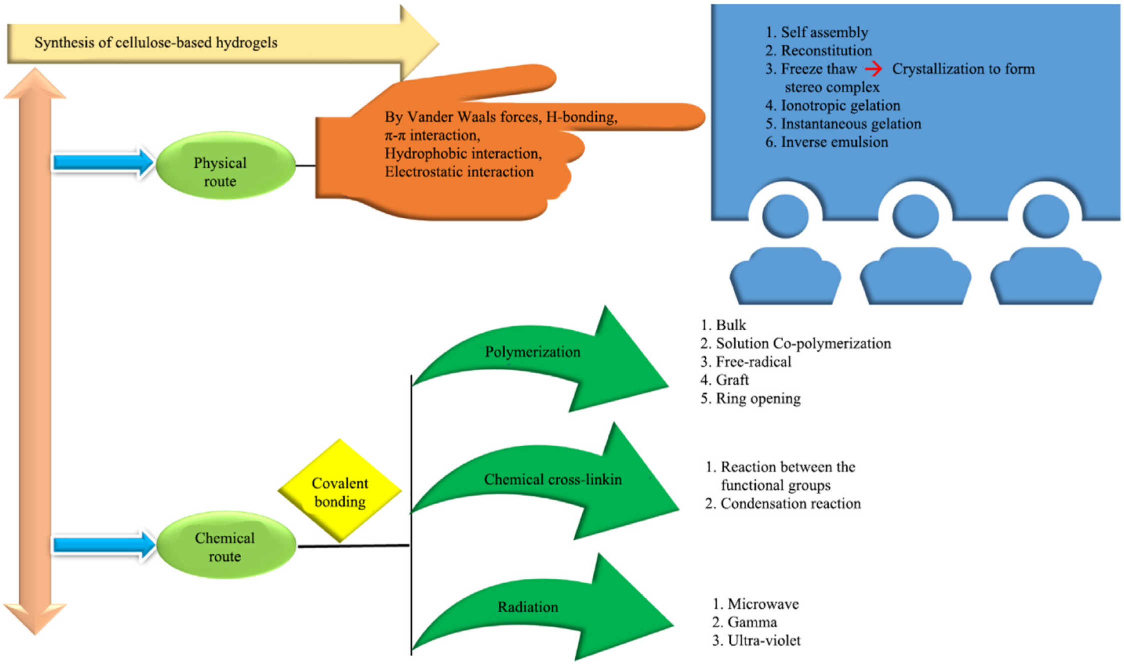


Fig. 3. Synthesis process of cellulose-based hydrogel.

Table 3
Various sources of nanocellulose with their average size.

	Cellulose nanocrystal	Cellulose nanofibril	Bacterial nanocellulose
Origin	Cotton, flax, wood, hemp, straw, etc.	Algae, straw, wood, hemp, tubers, cotton, bacteria, etc.	Alcohols and sugar
Average size (length × width)	(100–1 000) nm × (5 – 70) nm	Several μm × (5 – 60) nm	Several μm × (5 – 70) nm

Source: Wang, 2019.

adsorption of Pb (371 mg/g), which is higher than TiO_2 (20 mg/g). In follow-on work, Li et al. (2016) used CF/TiO_2 nanocomposite with a bed of fibrous membrane to adsorb Pb. For this purpose, he used a single-pass flow approach. The result showed that the adsorption capacity increased 9 times compared to the self-assembled bed and 13 times compared to the bare bed of CF.

Other physical arrangements of cellulose composites were also applied, such as beads, to enhance the adsorption capacity. Chitin/cellulose beads form through the coagulation process in which H_2SO_4 is used as a coagulating agent. Zhou et al. (2004) fabricated chitin/cellulose-based beads to adsorb Cu(II), Pb(II), and Cd(II) from an aqueous solution of thiourea and NaOH. The rate of adsorption of ions is Pd > Cd > Cu. Further, a cellulose composite was fabricated using cellulose acetate (CA) with sulphonated poly(ether imide) and poly(ethylene glycol) 600. This composite was used to adsorb heavy metals like Cd(II), Ni(II), Zn(II), and Cu(II). The order of adsorption is Cd > Zn > Ni > Cu (Nagendran et al., 2008; Barakat, 2011). A cellulose composite was fabricated using chitin with benzo-15-crown 5 in butyl methylimidazolium chloride, which exhibited enhanced adsorption efficiency and high mechanical strength. This is due to the synergistic consequences of combined materials compared to pure form (Mututuvari and Tran, 2014).

Cellulose can also be modified to work in a certain pH range. Qiu et al. (2014) examined ethyl cellulose composite's activity for removing Cr(VI) over a broad pH range of 3 – 11. Hokkanen et al. (2016) fabricated a cellulose composite using hydroxyapatite micro-fibrillated cellulose to adsorbed Cr(VI).

Nanocellulose is a lightweight material obtained from plants consisting of nano-sized cellulose fibrils. Nanocellulose is present in various forms like CNCs, CNFs, etc. Nanocellulose is eco-friendly and water-resistant due to film formation by counter-ion exchange (Rajinipriya et al., 2018). On average, the extraction of nanocellulose is problematic from the plant because of the presence of H-bonding and Vander Waals forces in cellulose. Extracting pure cellulose from plant matter requires pretreatment to remove wax, ash, hemicellulose, lignin, and other waste material. The process of cellulose-based materials extraction requires various steps as shown in Fig. 4. Various nanocellulose materials obtained from multiple sources with diverse particle sizes are shown in Table 3.

Nanocellulose is hydrophilic owing to multiple hydroxyl groups linked to its molecular spine. The existence of these hydroxyl clusters is an attractive characteristic when nanocellulose is used as a supporting representative within hydrophilic polymers. The hydrophilic character of nanocellulose allows dispersal in hydrophobic matrices (Missoum et al., 2013). The incompatibility of nanocel-

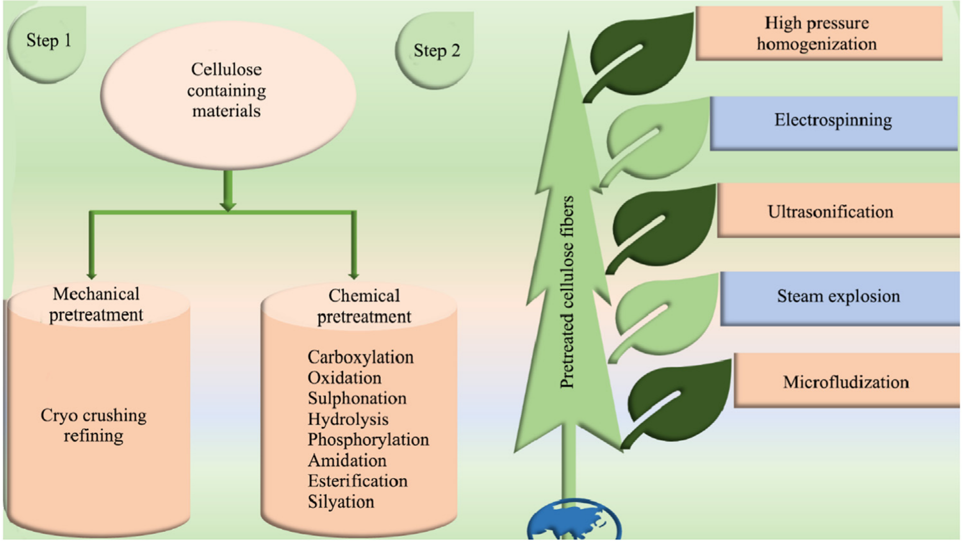


Fig. 4. Process of extraction of cellulose-based materials.

lulose with non-polar matrices disrupts the interfacial relations and eventually results in accumulation and phase partition. Consistent distribution of nanocellulose is important to obtain materials with enhanced mechanical characteristics. Therefore, widening the application of nanocellulose within numerous industrial areas requires further post-production efforts, such as esterification, chemical grafting, silylation, and oxidation, to develop the required surface features. Different methods (Fig. 5) are followed to tune the interfacial chemistry of nanocellulose to create the necessary hydrophilic-hydrophobic steadiness in a besieged environment (Dhali et al., 2021).

New tree-like cellulose-based nanofiber membranes have been synthesized using an electrospinning approach. For this purpose, tetra butyl ammonium chloride in small volumes was added within the CA, which further followed through deacetylation. The fabricated membrane exhibited a small size of pore, resistance toward solvents, and hydrophilicity with good mechanical properties (Zhang et al., 2018). The fabrication process is shown in Fig. 6a. The pore sizes of distinct nanofiber membranes were estimated. Compared to the typical nanofiber membrane, the pore size of a nanofiber membrane with a tree-like network was significantly reduced. As shown in Fig. 6b, the pore size of the common CA nanofiber membrane (C–CA) and deacetylated common CA nanofiber membrane (D-C-CA) membranes was 3.6 and 3.3 μm, while the pore size of CA tree-like nanofiber membrane (T-CA) and deacetylated CA tree-like nanofiber membrane (D-T-CA) membranes was 0.69 and 0.65 μm. The slight pore size reduction after deacetylation is due to a slight swelling of the nanofibers. The contact angle of C–CA and D-C-CA membranes (Fig. 6c_1 and 6c_2) were 74° and 11°, respectively. The T-CA membrane (Fig. 6c_3) had a hydrophilic contact angle of 62°, and the D-T-CA membranes (Fig. 6c_4) showed excessive hydrophilicity with a measured contact angle of 0° Fig. 6d illustrates the stress-strain arcs of the C–CA nanofiber membrane and T-CA nanofiber membrane before and after deacetylation. All the specimens were hot-pressed at 60 °C and 120 MPa for around 3 min. With respect to mechanical effects, the C–CA membrane retained a tensile strength of 1.9 MPa and elongation-at-break of 0.94 %. The tensile strength and elongation-at-break of deacetylated membrane were 1.83 MPa and 1.69 %, respectively. The different solvent resistance of the D-T-CA and the T-CA membrane is illustrated in Fig. 6e. The T-CA nanofiber membrane appeared to shrink and dissolve, while the D-T-CA nanofiber membrane had no change. This demonstrated that the performance of the D-T-CA nanofiber membrane was stable for separating organic solvents.

The adsorption of pollutants from wastewater depends on many conditions like temperature, pH, and time of contact with the adsorbent. Table 4 illustrates the possible cellulose modifications for wastewater treatment. For wastewater treatment, cellulose-based materials are essential and abundant. These materials show natural binding ability towards different applications. The adsorption of cellulose-based biopolymers can be improved by their pretreatment and then be further modified into valuable products.

Relationship between preparation of cellulose-based materials and water treatment

The relationship between the preparation of cellulose-based materials and water treatment is a fascinating and important intersection of science, technology, and environmental concerns.

Cellulose is the most abundant organic compound on earth and is commonly present in plants and some aquatic animals. It has received scientific and technological attention for its versatile applications in various industries such as the production of food, pharmaceuticals, paper, and textiles, etc., due to their widespread availability, low price, recyclability, biodegradability, and non-toxicity. Cellulose-based materials, often derived from renewable sources such as wood, cotton, or agricultural residues, possess unique properties that make them suitable for water treatment processes. These materials can be prepared and engineered in different forms, such as membranes, filters, adsorbents, and flocculants, to address various and specific water purification challenges.

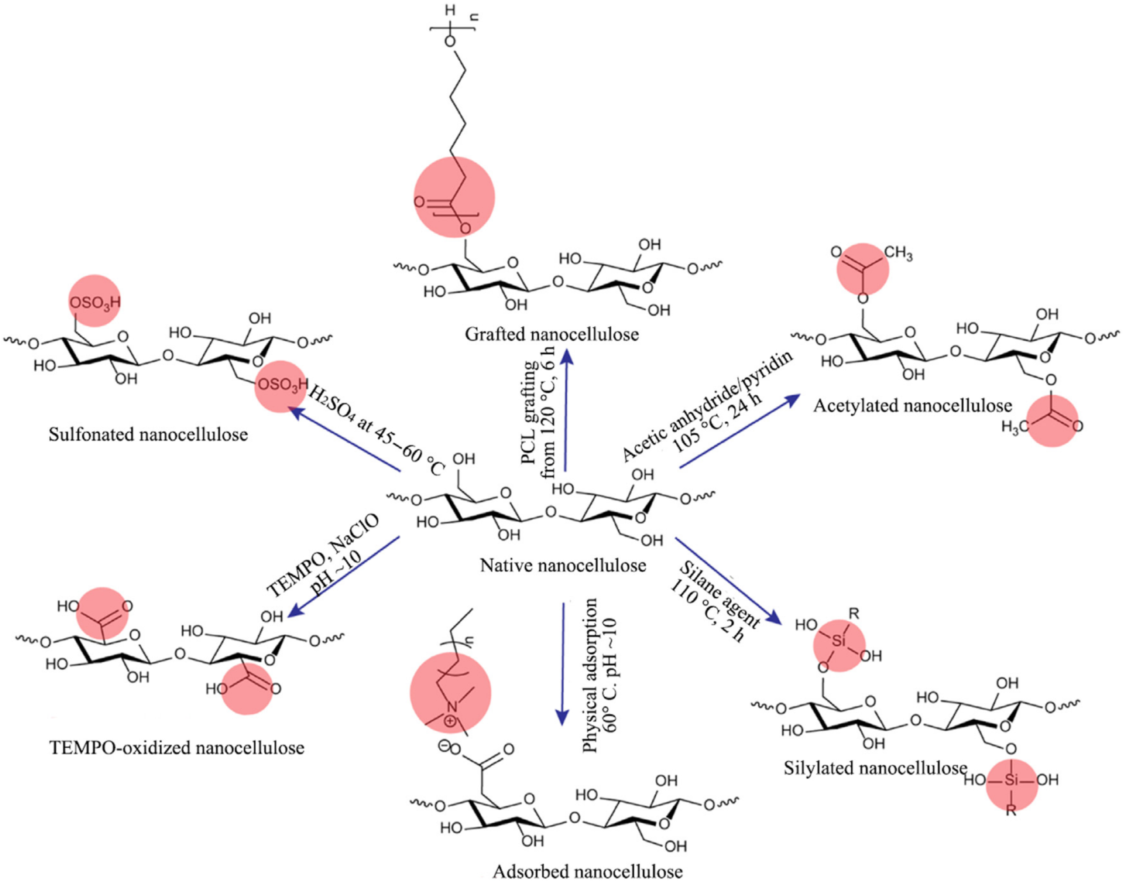


Fig. 5. Common surface modification methods used in nanocellulose production. The presented functional groups are marked in red (Dhali et al., 2021).

Table 4
Various types of modified cellulose composites with their specifications.

Modification in cellulose	Modified material	Removed impurity	Adsorption capacity	Reference
Composite beads	Chitosan	Cu(II)	0.84 mmol/g	Li and Bai, 2005
Nanocomposite material	Titanium dioxide (TiO_2)	Pb(II)	371.0 mg/g	Li et al., 2015
Composite material	Sodium montmorillonite	Cr(VI)	22.2 mg/g	Kumar et al., 2012
Magnetic nanocomposites of cellulose	Iron oxide	Pb(II)	21.5 mg/g	Xiong et al., 2014
Prepared hydroxyapatite microfibrillated cellulose composite	Calcium hydroxyapatite	Cr(VI)	2.208 mmol/g	Hokkanen et al., 2016
Composite material	Chitin/chitosan, ionic liquids	Cu(II) Pb(II) Zn(II) Ni(II) Cr(VI)	0.417 mmol/g 0.127 mmol/g 0.303 mmol/g 0.225 mmol/g 0.251 mmol/g	Sun et al., 2009
Cellulose and mercaptobenzothiazole composite	Mercapto benzothiazole	Hg(II)	204.08 mg/g	Krishna Kumar et al., 2013
Ethyl cellulose composites	Polyethylenimine	Cr(VI)	36.8 mg/g	Qiu et al., 2014
Collagen/cellulose beads composite	Bayberry tannin	Pb(II)	1.352 mmol/g	Zhang et al., 2015
Cellulose beads	Chitin, NaOH, H_2SO_4	Pb(II) Cd(II) Cu(II)	0.33 mmol/g 0.32 mmol/g 0.30 mmol/g	Vijayalakshmi et al., 2016

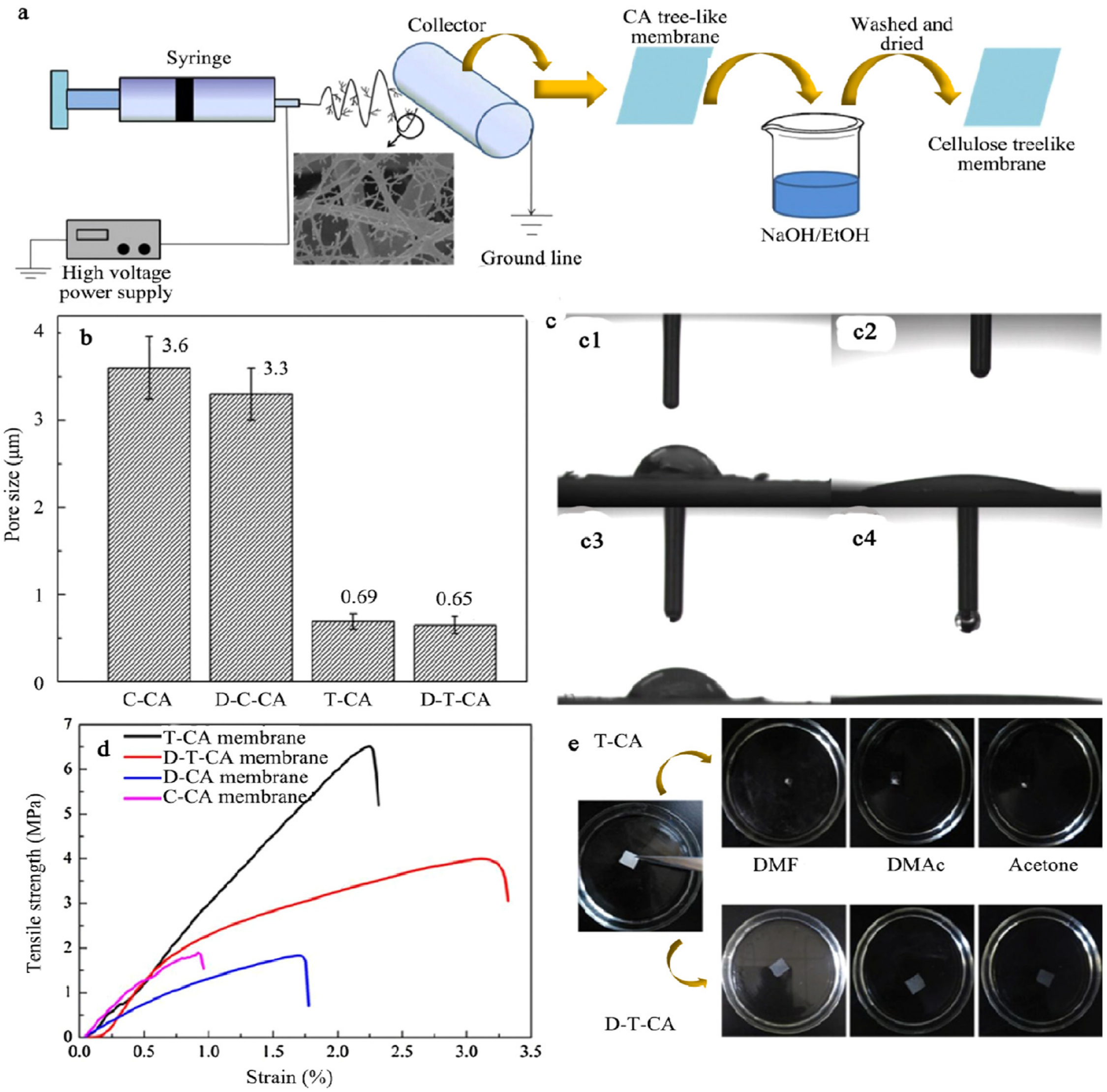
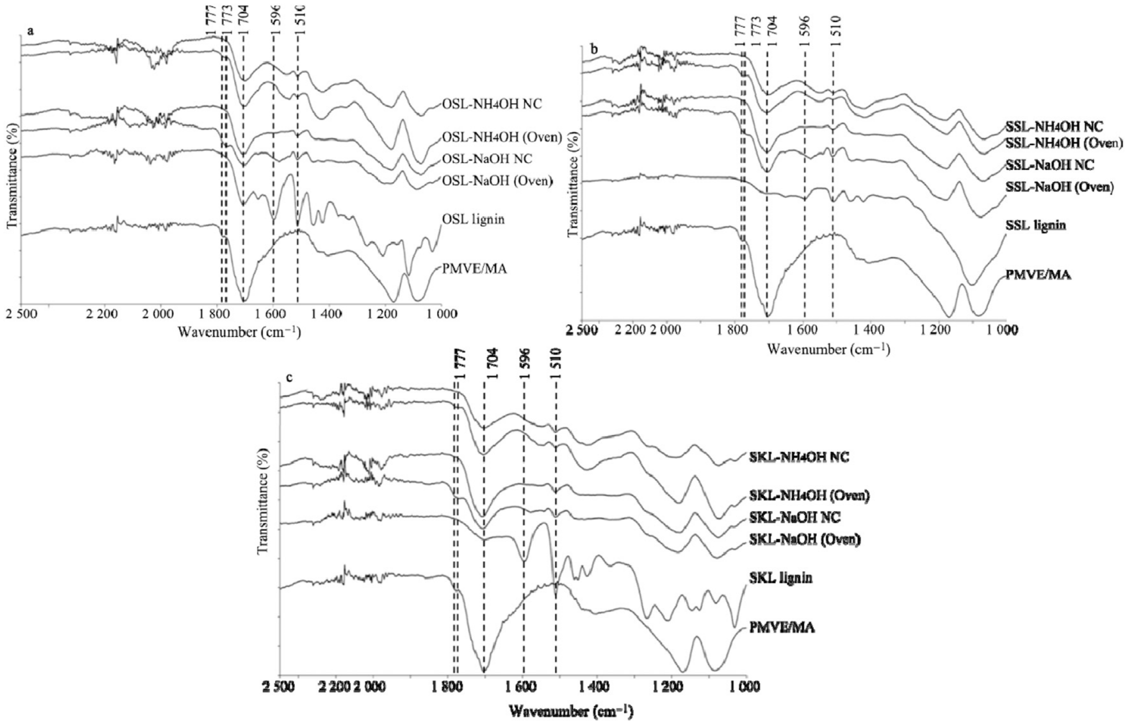


Fig. 6. (a) The new tree-like cellulose-based nanofiber membrane synthesis process; (b) Pore size distributions of various nanofiber membranes; (c) Pictures of the water contact inclination with distinct nanofiber membranes: (c_1) C–CA membrane, (c_2) D-C-CA membrane, (c_3) T-CA membrane, and (c_4) D-T-CA membrane; (d) Tensile-strain curves of various nanofiber membranes; (e) Optical photos of T-CA and D-T-CA membranes absorbed into DMF, DMAc, and acetone (Zhang et al., 2018).
CA: cellulose acetate; C–CA: common cellulose acetate nanofiber membrane; D-C-CA: deacetylated common cellulose acetate nanofiber membrane; T-CA: cellulose acetate tree-like nanofiber membrane; D-T-CA: deacetylated cellulose acetate tree-like nanofiber membrane; DMF: dimethylformamide; DMAc: Dimethylacetamide.

The use of renewable cellulose obtained from agriculture and biomass feedstock in wastewater treatment not only reduces carbon emissions but may also diminish the cost of wastewater treatment. The functionalization of cellulose by the -OH groups can significantly extend its applications in the treatment of wastewater (Peng et al., 2020). In their study of several cellulose-based adsorbents, Peng et al. (2020) confirmed that the various chemical modifications of cellulose by surface functional groups like -COOH, succinate, -NH_2, imidazole, -SH, amidoxime, thioether, -SO_3H, dithiocarbamate, xanthate, phosphate, etc. can significantly enhance their adsorption properties and selectivity towards removal of cations, anions, heavy metals etc. (Rocky et al., 2023).

Interaction mechanism of cellulose-based materials in water treatment

Cellulose-based materials can be characterized using advanced spectroscopy approaches and theoretical calculations to gain insights into their structure, properties, and interaction mechanisms (Mahmoodi et al., 2022). In this section, we summarise how these techniques are utilized.



OSL: wheat straw organosolv lignin; NC: non-crosslinked hydrogel; PMVE/MA: poly (methyl vinyl ether) co-maleic acid;
SSL: wheat straw soda lignin; SKL: softwood kraft lignin.

Fig. 7. Fourier transform infrared spectrum (Domínguez-Robles et al., 2018)
OSL: wheat straw organosolv lignin; NC: non-crosslinked hydrogel; PMVE/MA: poly (methyl vinyl ether) co-maleic acid; SSL: wheat straw soda lignin; SKL: softwood kraft lignin.

Infrared (IR) spectroscopy: IR spectroscopy is generally used to study cellulose-based materials to reveal the functional groups present in the material and their relations. By analyzing the absorption bands in the IR spectrum, investigators can determine cellulose-specific peaks, such as those associated with the cellulose backbone (e.g., C–O stretching), hydroxyl groups (-OH), and intermolecular hydrogen bonding (Raucci et al., 2015; Stricher et al., 2021). IR spectroscopy can also explore the influence of processing or changes on cellulose materials.

To remove cationic dye from wastewater, a biocompatible hydrogel was fabricated by crosslinking between lignin and poly (methyl vinyl ether) co-maleic acid (PMVE/MA) via ester linkages. A green synthetic process was used to form hydrogels, and the byproduct of the reaction was H_2O. Fourier transform infrared (FTIR) analysis was applied to establish the chemical property of crosslinking (Fig.7). For the PMVE/MA, the obtained spectra show bands at 1 704 cm^{-1} for the carbonyl group, 1 777 cm^{-1} for maleic anhydride. Further, ranges of the hydrogels treated over 80 ºC show two peaks of the carbonyl group: a peak at 1 773 cm^{-1} for the anhydride group and another peak at 1 708 cm^{-1} for the acid carbonyl group. In addition, a shift in the C = O peak was observed from 1 708 to 1 735 cm^{-1} showing the esterification process of the crosslinked hydrogels (Domínguez-Robles et al., 2018).

Raman spectroscopy: Raman spectroscopy is used to reveal data about molecular vibrations and crystal structure. Raman spectra can determine cellulose polymorphs (e.g., cellulose I and cellulose II) and show structural changes caused by processing or modifications (Schenzel et al., 2009; Kim et al., 2013). Raman spectroscopy is also sensitive to hydrogen bonding relations and can deliver insights into crystallinity and disorder in cellulose materials.

The X-ray Diffraction (XRD): XRD broadly defines the crystal structure and degree of crystallinity in cellulose-based materials. By studying the diffraction patterns, investigators can specify the structure of cellulose chains and evaluate the crystalline and amorphous areas (Garvey et al., 2005; Agarwal et al., 2017). XRD can also help explain differences in the crystal structure caused by different treatments or changes. Further, cellulose-based composites are fabricated by using a one-step hydrolysis method that consists of Bismuth (Bi) NPs, which are mainly nanoplates of Bi oxychlorides (BiOCl). The BiOCl biochar efficiently removes azo anionic dye and methyl orange dye by photocatalytic degradation and adsorption. Using scanning electron microscope (SEM) and high resolution-SEM, it was shown that the acquired material consisted of homogenous platelet/disk-similar shaped NPs (Fig. 8a) with a size of 15–25 nm and diameter within the scope from 55 to 160 nm, with an average of 95 nm. The pristine alkaline lignin-based biochar had a consistent configuration (Fig. 8b) of a not-densely compacted essence, where irregular cells and ruptures with onsets at the macro-scale appear. SEM images of the materials (Fig. 8c) showed that the network and morphology of either biochar or BiOCl NPs was very consistent, with the former acting as a material towards the NPs. The crystalline structure of the fabricated material was

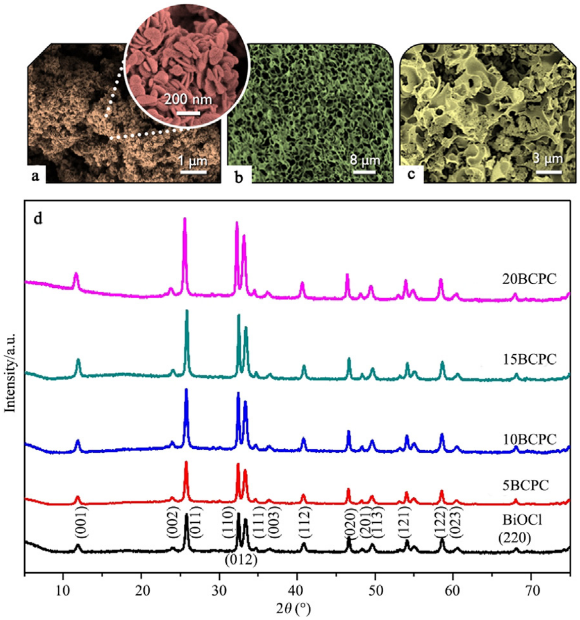


Fig. 8. Scanning electron microscope pictures of (a) BiOCl, (b) lignin-derived biochar, and (c) BiOCl biochar compound 15BCPC. (d) The XRD patterns of pure BiOCl NPs and their composites with various quantities of lignin-derived biochar (Singh et al., 2023).

examined by XRD, as shown in Fig. 8d. The XRD results of the pure BiOCl NPs fit well with the standard tetragonal data of BiOCl (JCPDS No. 85–861), with the individual reflection at (011), (110), and (012) to be the prime ones. As expected, the values of the textural parameters predictable from the N_2 sorption tests were not so high, which is in agreement with analogues described in the literature for the same class of materials. The BiOCl sample offered a specific surface of 19 m^2/g and a non-porous structure (total pore volume of 0.037 cm^3/g), with the formed "pores" to as a result of the formed inter-particles, inter-clusters, or/and inter-aggregate cages/spaces within the NPs (Singh et al., 2023).

Solid-state nuclear magnetic resonance (NMR) spectroscopy: Solid-state NMR spectroscopy is used to explore cellulose-based materials' local structural circumstances and dynamics. It provides data about molecular mobility, intermolecular interactions, and chemical shifts (El Hariri El Nokab et al., 2022). NMR can examine cellulose carbon environments, for example the cellulose spine and side groups, and observe changes resulting from chemical transformations or processing. In this way, the -OH groups were investigated using the quantitative 31P NMR technique published by two researchers Granata and Argyropoulos (1995). The NMR spectra were attained using a Bruker 500 MHz spectrometer (Billerica, MA, USA). The NMR parameters were 1 024 scans with a pulse delay of 5 s, 90 °C pulse and line boarding of 2 and default baseline correction. Further, a lignin-based bio-adsorbent was fabricated by ammonization and sulphonation of lignin, namely SAPL-1.5, that contained some particular functional groups with spatial cross-linking arrangements. To characterize SAPL-1.5, 31P, 1 H, 13C NMR are used and compared with bare lignin as shown in Fig. 9. The 31P NMR spectroscopy is a simplistic and straight analysis technique for calculating the -OH groups in carboxyl groups, phenolic hydroxyl, aliphatic hydroxyl, etc. for lignin. The intensity of the signals at $1.384–1.371 \times 10^{-4}$ denoting p-hydroxyphenyl components was noticeably improved compared to that of lignin, indicating that the phenol was very successfully grafted onto the lignin. By contrast, the intensity of the signals belonging to Al-OH in phenolated lignin ($1.46–1.49 \times 10^{-4}$) was noticeably decreased, which indicated that phenolate reactions take place in the side chain of lignin in an acidic medium (Wang et al., 2017a).

Theoretical calculations: Theoretical calculations like density functional theory, molecular dynamics, and Monte Carlo simulations, can complete practical spectroscopic approaches. These calculations can be used to understand cellulose-based materials' atomic-level structure, energetics, and mechanical effects (Ramezanzadeh et al., 2018; Qin et al., 2023). By modeling the relations among cellulose chains, solvents, additives, or other molecules, investigators can anticipate and comprehend the behaviour of cellulose-based materials under diverse circumstances.

The hybrid of advanced spectroscopy characterization approaches and theoretical calculations allows a thorough knowledge of cellulose-based materials, including their design, properties, and interaction mechanisms with other materials (Kaur et al., 2023b; Mishra et al., 2023a; Siwal et al., 2023). This understanding is essential for developing enhanced cellulose-based materials and their applications in different areas, such as packaging, textiles, biomedical materials, and renewable energy.

Applications of cellulose and other biobased materials in wastewater treatment

Cellulose-based materials have gained significant attention in recent years as a promising alternative for wastewater treatment due to their biodegradability, abundance, and sustainability. The unique properties of cellulose-based materials, such as their high

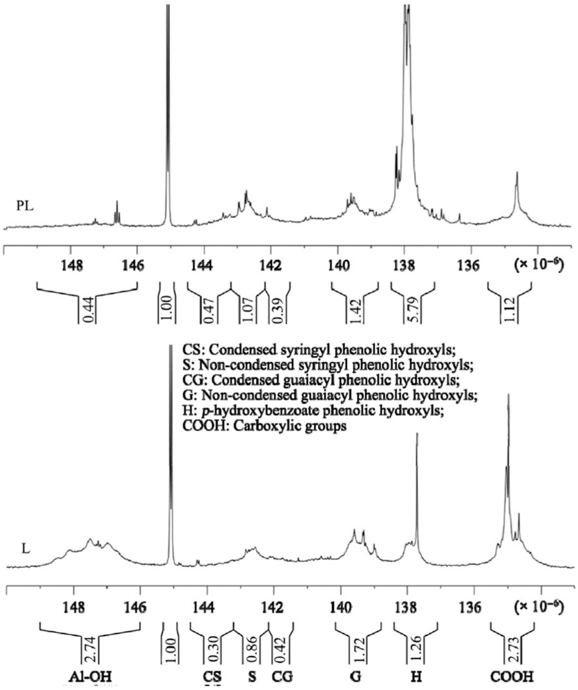


Fig. 9. The 31P nuclear magnetic resonance spectrum of lignin and phenolated lignin (Wang et al., 2017a).

surface area, porous structure, and surface charge, make them suitable for various applications in wastewater treatment (Kabir et al., 2018; Tu et al., 2021). One of the most common applications of cellulose-based materials in wastewater treatment is as adsorbents for removing contaminants such as heavy metals, organic pollutants, and dyes (Sajid et al., 2018). The high surface area of cellulose-based materials allows them to effectively adsorb these contaminants through various mechanisms such as electrostatic attraction, complexation, and ion exchange (Zare et al., 2021).

Cellulose-based materials have been explored as membranes for wastewater treatment. The porous structure of cellulose-based membranes allows for the selective separation of contaminants based on their size, shape, and charge. Furthermore, cellulose-based membranes can be modified to enhance their filtration efficiency and selectivity (Jamshaid et al., 2017; Jalvo et al., 2021). In addition to adsorption and membrane applications, cellulose-based materials have shown promise as catalysts for the degradation of organic pollutants in wastewater. Cellulose-based catalysts can be synthesized by incorporating metal nanoparticles or enzymes onto the surface of cellulose-based materials, which enhances their catalytic activity and stability (Liang et al., 2018). Cellulose-based materials can also be integrated with other technologies to improve their performance in wastewater treatment. For instance, cellulose-based adsorbents can be combined with photocatalysts to enhance their removal efficiency under UV light irradiation.

However, challenges such as the limited mechanical strength, chemical stability, and low reusability of cellulose-based materials must be addressed to achieve practical applications in wastewater treatment (Dong et al., 2021; Wu et al., 2022b). Ongoing research and development in this field aims to overcome these challenges and advance the utilization of cellulose-based materials for wastewater treatment, leading to sustainable and eco-friendly wastewater treatment technologies.

Freshwater can be polluted by various processes including industrial, agricultural, and domestic activity. This water contamination can harm humans and aquatic flora and fauna as it may consist of harmful chemicals like dye and heavy metals. Further, water can be polluted by the oil and petroleum industry, including its various stages like oil production, spilling oil during transportation, refining of oil etc. (Munirasu et al., 2016). These toxic effects imply a requirement for some suitable methods to treat industrial water before releasing it into water bodies. Water contains mainly three types of contaminants: inorganic matter, organic matter, and suspended solid particulate. Various processes like filtration, absorption, adsorption, flocculation etc., are used to treat wastewater. Adsorption mainly removes oils, organic matter, and heavy metals in contaminated water. Cellulose contains many hydroxyl groups on its surface and as such they can entrap chemical species and hence adsorb the pollutants over its surface (Varghese et al., 2019). Solid suspended materials are removed using the flocculation method. Solutions based on natural cellulose are effective, relatively cheap and control environmental pollution by decreasing the emission of carbon (Peng et al., 2020; Sayyed et al., 2021). Various wastewater treatment techniques are shown in Fig. 10 with different cellulose-based nanomaterials.

Removal of dyes

Dyes, used by various industries to colour materials, are the major pollutants that create many problems in humans, and have been linked to cancer and respiratory disorder and are harmful to the ecosystem (Kishor et al., 2021). There are numerous methods

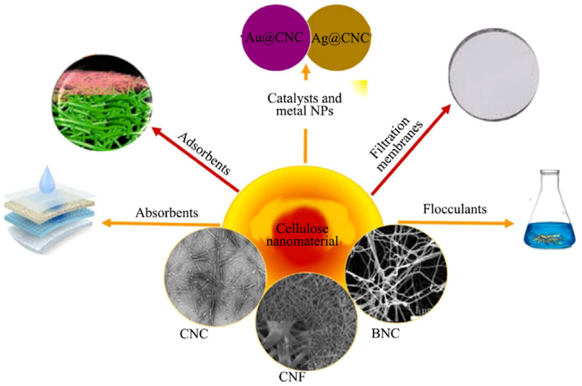


Fig. 10. Schematic representation of various wastewater treatment techniques from cellulose-based nanomaterials (Sayyed et al., 2021).

available to remove dyes from wastewater, but most are costly and some are known to release toxic byproducts. Removing dyes from wastewater using cellulose-based materials has achieved significant attention due to their superior adsorption capability and renewability. The cellulose-based materials are non-toxic, biodegradable, clean (non-polluting), and sustainable method for wastewater treatment (Siwal et al., 2021b; Mishra et al., 2023c).

Different forms of cellulose, like fibres, stalks, bark, seed, shell roots, are used as adsorbents. To eliminate dyes like methylene blue (MB) and basic blue 9, cellulose-based materials like garlic peel (Hameed and Ahmad, 2009), grass waste (Hameed, 2009a), and jackfruit peel (Hameed, 2009b) have been used to make adsorbent with capacities of 142.86, 457.64, 285.73 mg/g, respectively. To remove methylene red (MR) dye from contaminated water, Ahmad et al. (2019) fabricated a cellulose-based material with lemongrass leaf-based activated carbon. The result demonstrates an adsorption capacity of the dye was 76.923 mg/g at the pH over 2 for 5 h. It was found that with the increase in the dye concentration, temperature, and contact time, the MR dye adsorption rate increased. This indicates that the overall process is endothermic and occurs through physical adsorption.

Jawad et al. (2016) fabricated an adsorbent for the adsorption of MB dye from contaminated water. They used H_2SO_4-treated activated carbon obtained from the coconut leaf. The adsorbent had an irregular and rough surface with many cavities and gave a high adsorption capacity of 149.3 mg/g for MB dye. The adsorption efficiency increased further with the rise of the initial concentration of MB. On the other hand, Ding et al. (2014) fabricated an adsorbent by activated carbon obtained from rice husk to remove rhodamine B dye with an adsorption volume of 478.5 mg/g for 5 h. The pH of the solution did not affect the adsorption of the dye. Chemically activated carbon obtained from jute sticks was used to eliminate brilliant green dye from wastewater with an adsorption volume of 480 mg/g (Asadullah et al., 2010). In another study, guava leaf-based activated carbon was fabricated showing an adsorption capacity of 39.7 mg/g for removing congo red dye (Ojedokun and Bello, 2017). Using the orange peel, Lam et al. (2017) prepared activated carbon with an adsorption volume of 28.5 mg/g for the adsorption of malachite green dye. Further, to adsorb the bromophenol blue and bromothymol blue present in wastewater, raw maize cob are used with an equilibrium time of 125 and 110 min, correspondingly. The adsorption of dye corresponded with the Temkin isotherm model (Dada et al., 2020).

Siddiqui et al. (2019) fabricated a cellulose-based nanocomposite that acted as an adsorptive to eliminate MB dye from polluted water. The nanocomposite comprised antimicrobial Nigella sativa seed-based MnO_2 with black cumin (MnO_2/BC nanocomposite). The adsorption capacity for as-prepared nanocomposite for MB dye was 185.19 mg/g at 318 K and pH of 7. The adsorption procedure proceeds by Langmuir isotherm and endothermic in nature. During the adsorption of MB over the surface of MnO_2/BC nanocomposite, hydrogen bonding and electrostatic attraction occurred between the dye and the surface.

Using exhausted coffee ground powder, rhodamine 6 G and rhodamine B adsorption was demonstrated from wastewater with adsorption capacities of 17.4 and 5.3 mg/g, respectively (Shen and Gondal, 2017). It was found that the adsorption of rhodamine dye over the surface of the adsorbent occurs through hydrophobic, electrostatic, and intermolecular interactions. Platanus oriental leaf powder (Peydayesh and Rahbar-Kelishami, 2015), pineapple leaf powder (Chowdhury et al., 2011), and pine tree leaves (Deniz and Karaman, 2011) were used as adsorbents for the elimination of MB dye, basic green 4, and basic red 46 dye correspondingly. Their maximum removal capacity is 114.94, 48.72, and 71.94 mg/g with a contact time of 70, 150, and 120 min, respectively. Neem leaf powder has also been reported for the adsorption of brilliant green dye, the adsorption capacity is 0.554 mmol/g for 240 min (Bhattacharyya and Sarma, 2003).

Lignin and lignocellulose-based gels are also used to remove dye from wastewater with some modification. Lignin-based lignocellulosic gel with a porous arrangement due to combination with 3-aminopropyltriethoxysilane is used to remove rhodamine B and MB dye. The adsorption capacity for lignin-containing sample is 192 mg/g, and for rhodamine B is 201 mg/g, which is higher than lignin-free materials, the process of adsorption proceeds through the chemisorption process (Zhang et al., 2019a).

Wang et al. (2017c) used a lignin-based hydrogel synthesized by combining it with acrylamide and N-isopropyl acrylamide to eliminate MB dye from wastewater. The process of adsorption was highly reliant on temperature and pH. The hydrogel has regeneration ability and can be used 5 times without performance decrease. For the removal of MB dye, a lignin/graphene-based aerogel was fabricated, in which cross-linking was done by chitosan. The aerogel removed up to ≥ 99% MB dye with an adsorption capacity

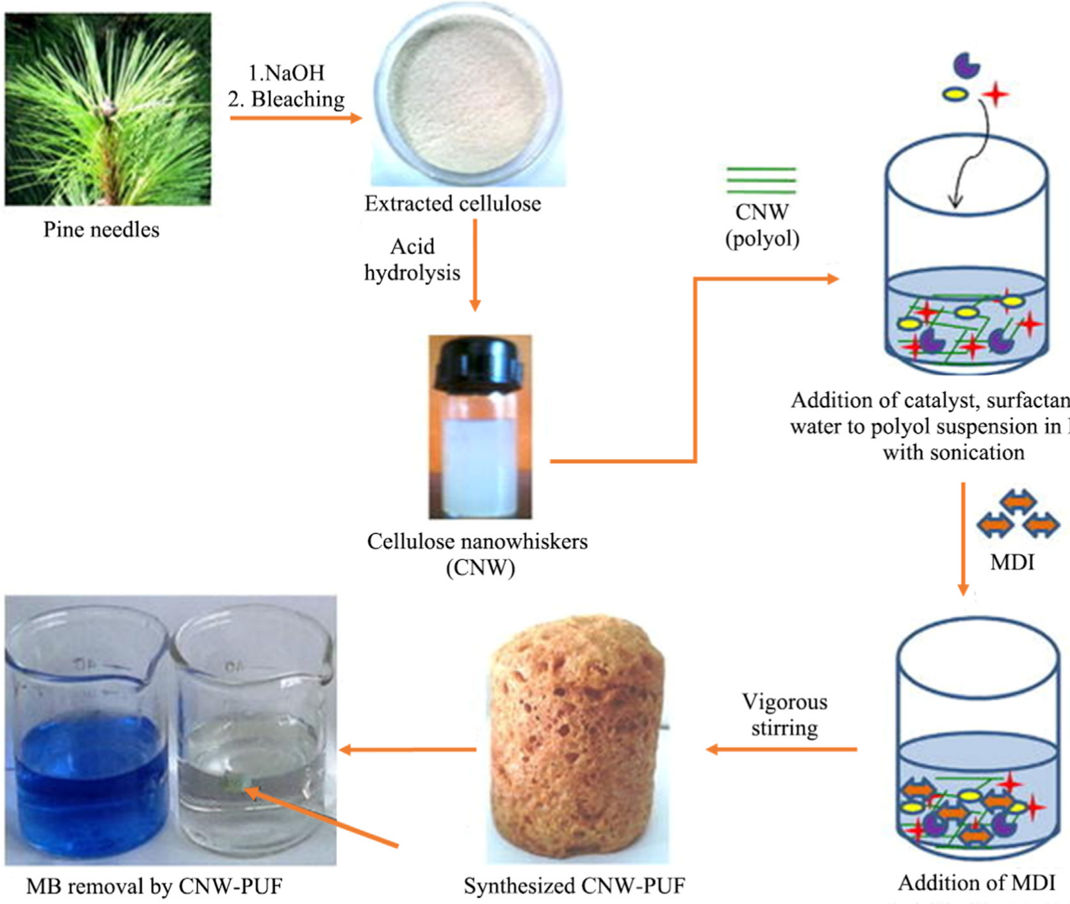


Fig. 11. Fabrication process of CNWs-PUF from pine needles with its approach to removing MB dye (Kumari et al., 2016)
MDI: 4,40-diphenylmethane diisocyanate; PUF: polyurethane foam.

of 1 023.9 mg/g (Yan et al., 2019). While through the thermodynamic analysis, it was found that dye adsorption is an endothermic and spontaneous process. During the adsorption, hydrogen bonding, electrostatic interaction and π-π stacking occur between MB dye and lignin-based aerogel.

Cellulose nanowhiskers (CNWs) are also used to remove dye from waste and contaminated water. Kumari et al. (2016) produced a novel polyurethane foam (PUF) using CNWs. The acidic hydrolysis of cellulose was done from needles of pine plants and diphenylmethane diisocyanate. The PUF was used to remove MB dye from water effluents. It was observed that MB dye was wholly removed within 20 min at 55 °C. The absorption capacity of PUF was 554.8 mg/g, and it was regenerated and used for many cycles, the complete process of PUF fabrication with its working mechanism is shown in Fig. 11.

Removal of oil

In the oil and petroleum industry, water can be produced and polluted at every step of processing. Within the oil value chain, processing contributes approximately 10 % of polluted discharge with the remaining 90 % coming from transportation, pipelines, offshore platforms, etc. These consequences may be short-term or long-term (Aguilera et al., 2010; DeLaune and Wright, 2011). There is a need to develop more efficient and capable technologies to resolve the pollution problem related to oil spills and as such this area remains an active area of academic and industrial research (Adebajo et al., 2003; Corsellis et al., 2016).

The oil industry has two types of water: produced and processed. Contaminated water obtained during extraction consists of a mix of H_2O, minerals, dispersed oils, chemicals related to production, and dissolved gases (Veil et al., 2004). Compared to processed water, produced water has more mineral ions in dissolved form. Harmful chemicals in the wastewater, like NH_3, C_6H_5OH, H_2S, benzene, toluene, ethylbenzene, and xylenes are commonly known as BTEX (Munirasu et al., 2016). The oil in the water makes a layer over the surface due to its hydrophobicity. The formation of an oil layer is harmful to aquatic and marine life. Various advanced techniques can remove the oil present in the water. Cellulose-based materials are popular due to their wide availability, low cost, and biodegradable ability.

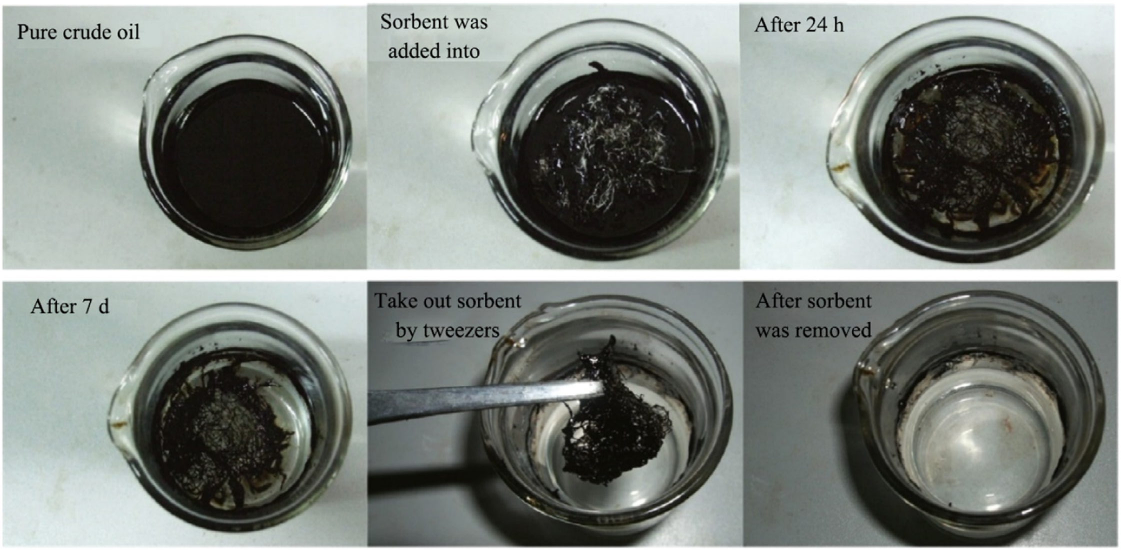


Fig. 12. Oil adsorption process of corn straw modified acetylated cellulose fibres (Li et al., 2013).

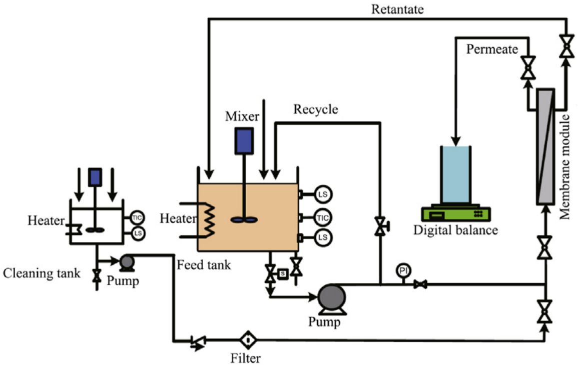


Fig. 13. Diagrammatic representation of cross-flow filtration process as performed in the laboratory (Madaeni et al., 2013).

Li et al. (2013) investigated modified cellulose fibres obtained from corn straw as a sorbent for oil from contaminated water. The cellulose fibres extracted from corn straw were acetylated to enhance their hydrophobicity. This prepared material shows oil sorption capacities of 42.53 g/g for pump oil, 52.65 g/g for diesel oil, and 57.64 g/g for crude oil at 25 °C for 1 h. The oil sorption procedure by corn straw-modified cellulose fibre is shown in Fig. 12. In this method, oil's cellulose fibre absorption is increased using an acetylation process that modifies the lipophilic surface of cellulose fibres.

Nguyen et al. (2013) fabricated cellulose-based aerogels which act as super absorbents for oil from contaminated water. For this purpose, they treated cellulose fibres with NaOH/ NH_2CONH_2 solution. The fibres were placed in a refrigerator for the gelation and then mixed in C_2H_5OH for coagulation. The solvent exchange process was done using deionized water, and the resultant mixture was freeze-dried for two days. After that, aerogel salinization was done using methyl trimethoxy silane (MTMS) over 343.15 K for 2 h. The highly porous, MTMS-doped, low-density cellulose-based aerogel led to superior oil sorbent capacity.

The effect of temperature was also examined. It was found that the higher sorption capability for rice bran crude oil was 24.4 g/g over 313.15 K. The cellulose aerogel regenerated coated with MTMS has a good affinity towards crude oil and acts as a suitable adsorbent for treating oil spills. Besides the adsorption approach, membrane filtration technique is reported as an excellent method to remove oil from wastewater (Zhang et al., 2014b). In the semi-batch process, the infused membrane was continued to be withdrawn, and the oil-improved non-permeate was reprocessed as shown in Fig. 13 (Madaeni et al., 2013).

Using cerium ion as initiator, CA and polyacrylonitrile were combined by a free radical polymerization process, and the ultrafiltration membrane CA-graft polyacrylonitrile (CA-g-PAN) was synthesized (Chen et al., 2009). The prepared CA-g-PAN exhibited superior permeability and excellent antifouling characteristics for the separation of oil/water emulsion.

It was observed that polyacrylonitrile, which is hydrophobic, increased the membrane pore size, resulting in enhanced permeation. The antifouling property of the prepared membrane was examined by flux recovery and flux decay ratio of oil/water emulsion. It was found that CA-g-PAN membranes showed 100 % removal capacity under different experimental conditions. Another group of

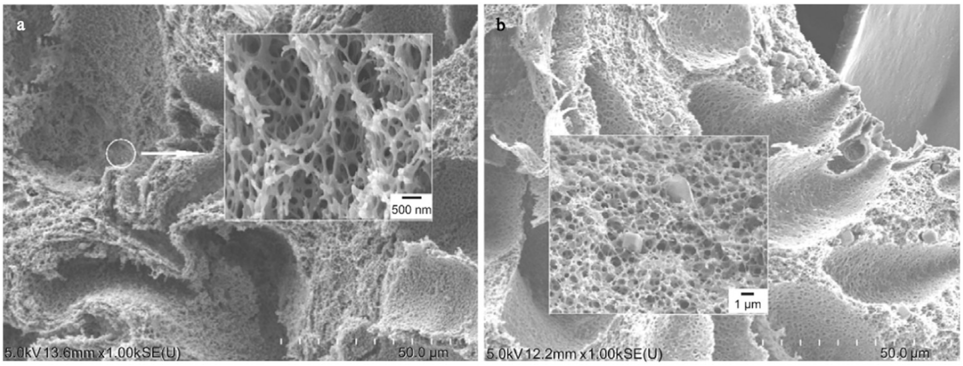


Fig. 14. Scanning electron microscope (SEM) pictures of (a) CA fibre and (b) CA/Z fibre (Ji et al., 2012).

researchers synthesized an ultrathin nanoporous cellulose-based membrane. For this purpose, they performed freeze-extraction of a heavily-diluted cellulose solution. This membrane was used to separate a nano emulsion of oil-in-water. The membrane had a thickness of 80–220 nm and a 10–12 nm cut-off. The membrane showed an ability of water permeation of 1 620 L/(m^2 h bar) with good size-selective separation characteristics. The efficiency for oil removal from nano emulsion is 96.5 % for the drops with a size of 200.4 nm (Zhou et al., 2014).

Removal of heavy metals

Cellulose-based materials suggest different advantages for heavy metal removal, such as their abundance, renewability, biodegradability, and versatility. Nevertheless, it is essential to assess the specific features of the heavy metals and the wastewater and the optimal processing necessities to maximize heavy metal removal efficiency utilizing cellulose-based materials. Various processes are reported to remove the heavy metals from wastewater such as chemical precipitation (Ku and Jung, 2001), ion exchange (Alyüz and Veli, 2009), membrane filtration (Landaburu-Aguirre et al., 2009), reverse osmosis (Shahalam et al., 2002; Mohsen-Nia et al., 2007), electrodialysis (Nataraj et al., 2007; Sadrzadeh et al., 2009), and adsorption (Park et al., 2007; Zhou et al., 2012a).

The cellulose was modified with maleic anhydride by Zhou et al. (2012a) and employed as an adsorbent to eliminate Hg(II) from wastewater. The outcomes showed that the prepared adsorbent exhibited superior adsorption capacity, i.e., 172.5 mg/g. Further, various experimental conditions like temperature, pH, contact time, were also investigated.

Thirumavalavan et al. (2010) showed the elimination of heavy metal ions from wastewater, like Cu(II), Zn(II), Cd(II), Ni(II), and Pb^{2+} by using three different kinds of cellulose-based materials like orange peel, banana peel, and lemon peel. For this purpose, chemical modification was performed over the lemon peel and cellulose surfaces using activated carbon. The Cu(II) and Ni(II) ions were adsorbed preferentially compared to other ions. While comparing the different adsorbents, it was found that surface-modified lemon peel cellulose exhibited increased adsorption capability. The order of adsorption ability is lemon peel cellulose with activated carbon > lemon peel cellulose > activated carbon > lemon peel, using the wet spinning approach.

Ji et al. (2012) fabricated a cellulose composite fibre, i.e., CA/zeolite composite fibres (CA/Z). In this process, zeolite particles were embedded over the surface of CA, which acted as the polymer matrix. The SEM images (Fig. 14) show the morphology of CA and CA/Z fibres. CA fibres have a porous structure with a 300–500 nm pore size, while zeolite particle size is 1 µm.

As a result, the zeolite particles are retained within the CA/Z fibre network. The result shows that the CA/Z fibres with an average pore size of 24.6 nm allow all the heavy metal ions to pass for direct contact with the zeolite adsorptive site. These CA/Z fibres remove Cu(II) and Ni(II) ions from the wastewater using Langmuir adsorption isotherm. The adsorption capacity of CA/Z fibres is 28.57 mg/g for Cu(II) and 16.95 mg/g for Ni(II) at 25 °C, which can be regenerated over 5 cycles.

To eliminate heavy metals, Wang and Wang (2016) prepared a polyvinyl alcohol (PVA) and CMC hydrogel (PVA/CMC) via a freeze-thaw approach to mix PVA and CMC in different ratios and then frozen and melted in five different cycles. To measure the adsorption capacity of metal ions, i.e., Ag(I), Cu(II), Zn(II) and Ni(II), samples were immersed for 1 day in 0.01 % metal ion solution at 288 K. PVA/CMC showed good adsorption of Ag(I) ion compare with other metal ions because Ag(I) had small size and could quickly diffuses through the polymer network.

Removal of radioactive materials

Nuclear energy is now widely regarded as a green energy source due to the very low emission of greenhouse gases. Nuclear energy has ultra-high energy density and has a key advantage of offering a dispatchable baseload for power generation (Antal and Karhunmaa, 2018; Sovacool et al., 2020; Ahmad, 2021). Due to advancements and potential growth in nuclear energy, concerns arise related to the issue that could harm society due to the release of mining wastewater which contain uranium and other radioactive substances. In the extreme, radioactive materials can also be result within wastewater due to nuclear accidents like as evinced at Chernobyl and Fukushima (Song et al., 2014; Wang et al., 2018; Kong et al., 2020).

Radioactive materials contained in wastewater can be very harmful to humans and the environment due to radionuclides' ultrahigh biological and chemical toxicity. This toxic effect leads to cancer organ damage with teratogenicity (Zhang et al., 2019b; Wang et al., 2020a). Therefore, there is an urgent requirement for some practical methods that remove these radionuclides from contaminated water. There are several ways to remove the radioactive waste from contaminated water such as ion exchange (Manos and Kanatzidis, 2012), extraction (Ahmad et al., 2020), chemical precipitation (Vigier et al., 2016), adsorption (Zhao et al., 2019), and membrane separation (Luo et al., 2019; Yang et al., 2022). The adsorption of these known methods has advantages of good economics, simplicity, and reusability with high decontamination ability. Various adsorbents are used to decontaminate radioactive wastewater, i.e., polymers, metal-organic framework, graphene, covalent organic frameworks, proteins, MXene, polypeptides etc. However, these synthetic materials have some limitations which may have their own adverse impacts on the environment (Li et al., 2018a; Deshwal et al., 2023).

Cellulose-based adsorbents are used to overcome the limitations of synthetic materials to treat radioactive wastewater. Cellulose-based materials are biodegradable and hydrophilic with antimicrobial property (Bai et al., 2020; Liu et al., 2021). However, cellulose does not contain sufficient functional groups to remove radioactive elements like uranium. For this purpose, natural cellulose have been modified by many researchers to increase the number of adsorption sites by introducing phosphonate, amine, and dialdehyde groups, which are widely used to capture uranium (Wu et al., 2022a).

In addition, a number of cellulose-based adsorbents derived from natural cellulose fibres like hemp fibres (Bai et al., 2020), bamboo fibres, and sisal fibres (Wang et al., 2020b) have been suggested. These may not be the most effective options due to their low specific surface areas, limited exposed reactive groups, and nonporous morphology. Other cellulose-based materials, such as sugarcane bagasse, lemon peels, pineapple peels, and coconut coir, are used to fabricate adsorbents through milling. These cellulose nanomaterials adsorbents have been used to remove radionuclides from contaminated water.

Rethinasabapathy et al. (2018) fabricated a composite known as FeAC/CMC/POSS by using Fe-amino clay, CMC, and polyhedral oligomeric silsesquioxane. This composite was used to adsorb Cs(I) from contaminated water. FeAC/CMC/POSS shows incredible adsorption ability of 152 mg/g for Cs(I), which may due to their layered morphology (Fig. 15a) and amino groups over the clay surface. In addition, the presence of carboxylate and hydroxyl groups on the surface of CMC might resulte in electrostatic attraction and ion-exchange mechanisms as shown in Fig. 15b.

Banana peels are also used to remove radioactive Th and U from polluted water. In a study, banana peels are converted into nano size (up to 12 nm) via milling, and used to remove radionuclides by binding with amine and carboxylic groups. It was observed that around 0.01−0.3 g of banana peels effectively remove 99.99 % Th(IV) from 100 mg/L, 18.8 mg/L initial concentration, and 70 % U(VI) from an initial concentration of 100 mg/L, 58.8 mg/L from synthetic and real polluted mine water, respectively (Oyewo et al., 2016). Ma et al. (2012) fabricated the ultrafine CNFs from wood pulp as an effective adsorbent for removing radioactive UO_2^{2+} from contaminated water. The wood pulp was chemically oxidated with 2,2,6,6-tetramethylpiperidine-1-oxylradical (TEMPO), sodium bromide, and sodium hypochlorite after mechanical disintegration. When the CNF suspension was added in UO_2^{2+} containing water, an interaction occurs between the -COO- of CNFs and UO_2^{2+} and forms a gel. The highest adsorption power of these ultrafine CNFs for UO_2^{2+} was 167 mg/g.

As shown in Fig. 16, cellulose-based nanomaterials are used in diverse forms to treat contaminated or polluted water, e.g., as a catalyst, adsorbent, membrane, flocculant, etc.

The extracts obtained from plants cells such as bacteria, fungi, actinomycetes, yeast, and algae are used for the synthesis of various bionanomaterials that are less costly and nontoxic (Mohanpuria et al., 2008; Schröfel et al., 2014; Zhang and Liu, 2020). As shown in Fig. 17, the bionanocomposites could give us an appealing substitute for removing radioactive ions of contaminated water from nuclear leakage.

Cellulose-based materials are very useful for developing countries to treat contaminated water because cellulose can be obtained naturally. For the large-scale implementation of these cellulose-based materials for adsorption of dye, heavy metals, radionuclides, pharmaceutical waste, oil removal, etc., more research is required.

Removal of other pollutants

Besides dye, oil, and heavy metal, wastewater also contains various undesirable inorganic pollutants, organic pollutants, and suspended particulate matter. These pollutants can be removed from wastewater using flocculation, filtration, adsorption, etc.

Suopajärvi et al. (2013) explored the flocculation of five different dicarboxyl cellulose (DCC) samples by cumulative levels of carboxylation. The reaction occurs among sodium periodate to prepare the DCC bleached birch chemical wood pulp and sodium chlorite. CNCs were fabricated with different carboxyl amounts, i.e., 0.38, 0.69, 0.75, and 1.75 mmol/g. The CNCs having 1.75 mmol/g carboxyl can remove turbidity (80 %) and chemical oxygen demand (60 %) from wastewater.

Additionally, Suopajärvi et al. (2014) examined a sulphonated CNC as a flocculating agent. Cellulose was attached with $–SO_3H$ group (Liimatainen et al., 2011) and the removal of turbidity was examined using 25 mg/L of $Fe_2(SO_4)_3$ to enhance the flocculation process. It was found that the CNCs had sulphonation and was helpful in removing turbidness from water at 2.5 mg/L.

By using DCC, Zhu et al. (2015) also studied the removal of turbidity from wastewater. Cellulose was prepared by adding NaOH and urea into bamboo pulp for 90 min at −12 ºC. The cellulose was mixed with $NaIO_4$ for 5 h; the extra $NaIO_4$ was broken down by ethane-1,2-diol, and the remaining solution was cooled at room temperature. By continuing the reaction, DCC is produced, having a carboxyl amount of 2.57 mmol/g. This DCC can remove up to 99.5 % of turbidity from a solution of kaolin (500 mg/L) when 25 mg/L DCC was used with 300 mg/L $CaCl_2$.

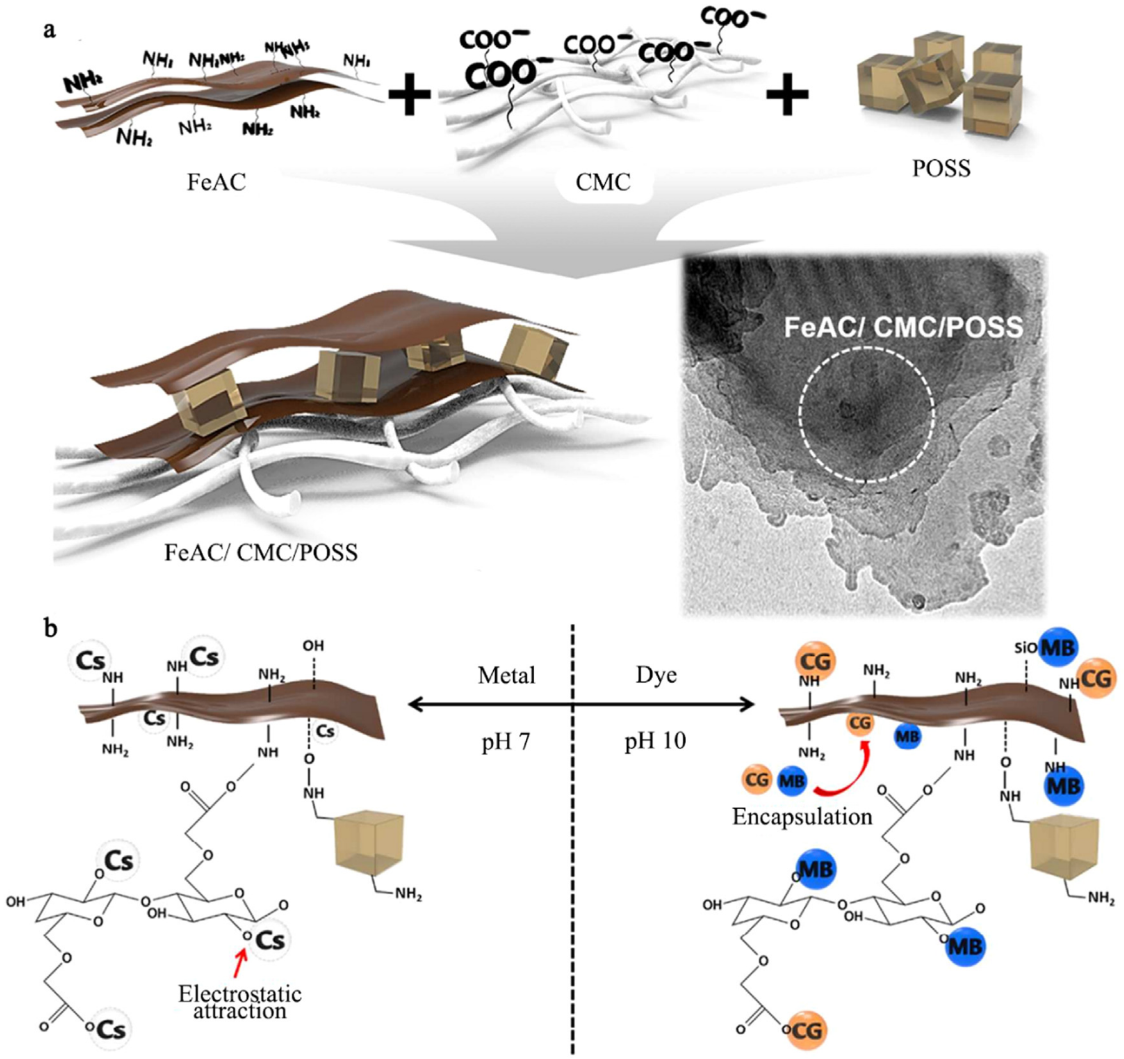


Fig. 15. (a) Schematic formation of FeAC/CMC/POSS and (b) adsorption mechanism of Cs by FeAC/CMC/POSS (Rethinasabapathy et al., 2018) FeAC: Fe-amino clay; CMC: carboxymethyl cellulose; POSS: polyhedral oligomeric silsesquioxane.

Alila and Boufi (2009) used an adsorbent to remove aromatic organic compounds from wastewater. A long hydrocarbon chain was added over a heterogeneous atmosphere to modify cellulose. For this purpose, N, N′-carbodiimidazole and 4,4′-methylene bis (phenyl isocyanate) were used to introduce the hydrocarbon chain in cellulose for modification. The cellulose fibres were modified using linear octyl anhydride and heterogeneous esterification. The modified material exhibited a high adsorption rate of 300 mol/g for organic compounds (aniline, benzene, nitrobenzene, mono or poly-substituted chlorobenzene, etc.) in water (Aloulou et al., 2006).

Pollution of water with F^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, and NO_2^- is harmful to the health of humans. These species are known as anionic species. F^- penetrates the skin of humans and converts hydroxyapatite $[Ca_{10}(PO_4)_6(OH)_2]$ of bones and teeth into fluorapatite $[Ca_5(PO_4)_3F]$ by dissolving in it. To adsorb these anionic pollutants or remove these anionic pollutants, cationic cellulose or cellulose-based nanocomposites are mainly used. Anions like NO_3^- and F^- are effectively adsorbed by the cationic CNFs.

It was reported by Pei et al. (2013) that the adsorption of anionic dyes present in wastewater by CNFs was increased by adding trimethyl ammonium chloride. Sehaqui et al. (2016) fabricated the cationic CNFs using waste pulp residue containing positively charged quaternary ammonium groups. For this purpose, esterification of pulp was done with glycidyl trimethyl ammonium chloride, after that, mechanical disintegration was performed. The obtained material has a 1.2 mmol/g cationic charge amount. The as-prepared quaternary ammonium CNFs showed high adsorption of SO_4^{2-} and PO_4^{3-} as compared to F^- and NO_3^-.

Pollutants, such as antibiotics, pharmaceutical waste, cosmetics, and drugs are soluble in water and known as miscible pollutants. The miscible organic contaminants can be removed from water by adsorption or by breaking down into parts using techniques like UV–visible photocatalysis, redox reactions, and ozonation. For the adsorption of pharmaceutical products like paracetamol, N, N-diethyl-

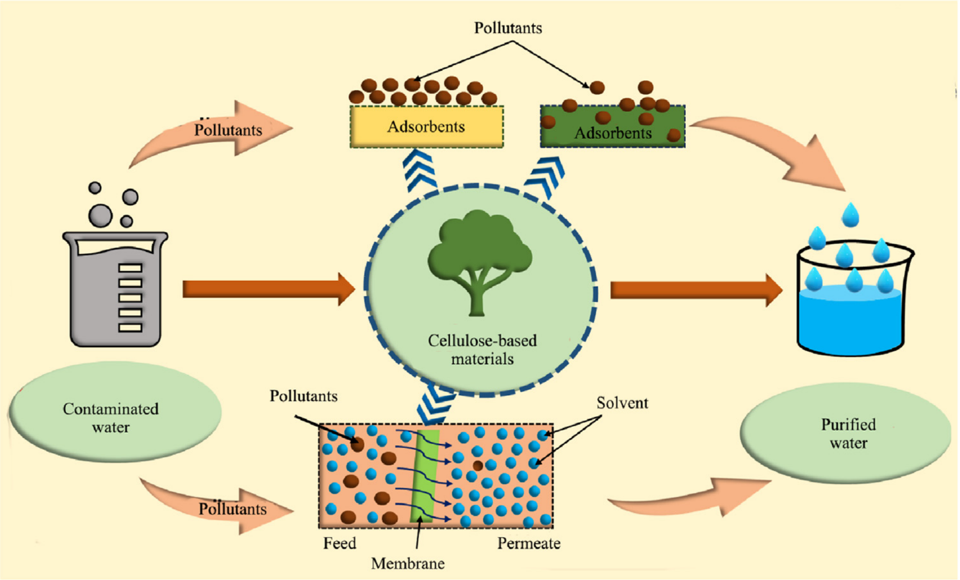


Fig. 16. Scheme of the water/wastewater treatment process mechanism based on cellulose-based materials.

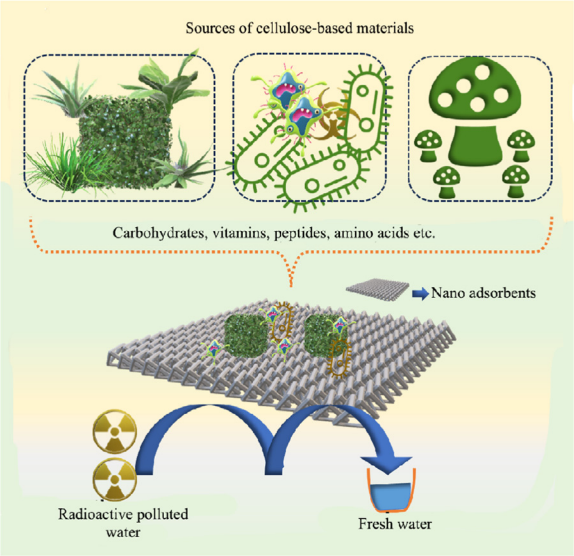


Fig. 17. Cellulose-based materials used for treatment of radioactively contaminated water.

meta-toluamide, sulfamethoxazole, nanocellulose in combination with Jeffamine ED 600 (a block copolymer) was fabricated, the adsorption process of this material based on electrostatic attraction (Herrera-Morales et al., 2017).

The CNC is also used to remove insecticides like chlorpyrifos from contaminated water. Chemometric examination shows a requirement of ~1.5 g/L nanocellulose in 20 min to adsorp 5 mg/L chlorpyrifos pesticide, offering an efficiency of 99.3 % (Moradeeya et al., 2017). In addition, to adsorp aspirin and tetracycline hydrochloride, a material consisting of UiO-66, BC, and polydopamine was fabricated. Outstanding adsorption ability was found by material for aspirin (149 mg/g) and tetracycline hydrochloride (184 mg/g). The fabrication process of the material with adsorption mechanism is shown in Fig. 18.

Advantages and disadvantages of cellulose based materials for wastewater treatment

Cellulose-based materials have numerous advantages as they are abundant natural biopolymers with many functional groups. The functional group present in these materials like -COOH, -OH can be used to react with several nanoparticles (NPs) like Ag-NPs, graphene oxide, ZnO NPs, and MOFs, and can be applied to various applications according to requirement. In the case of the water

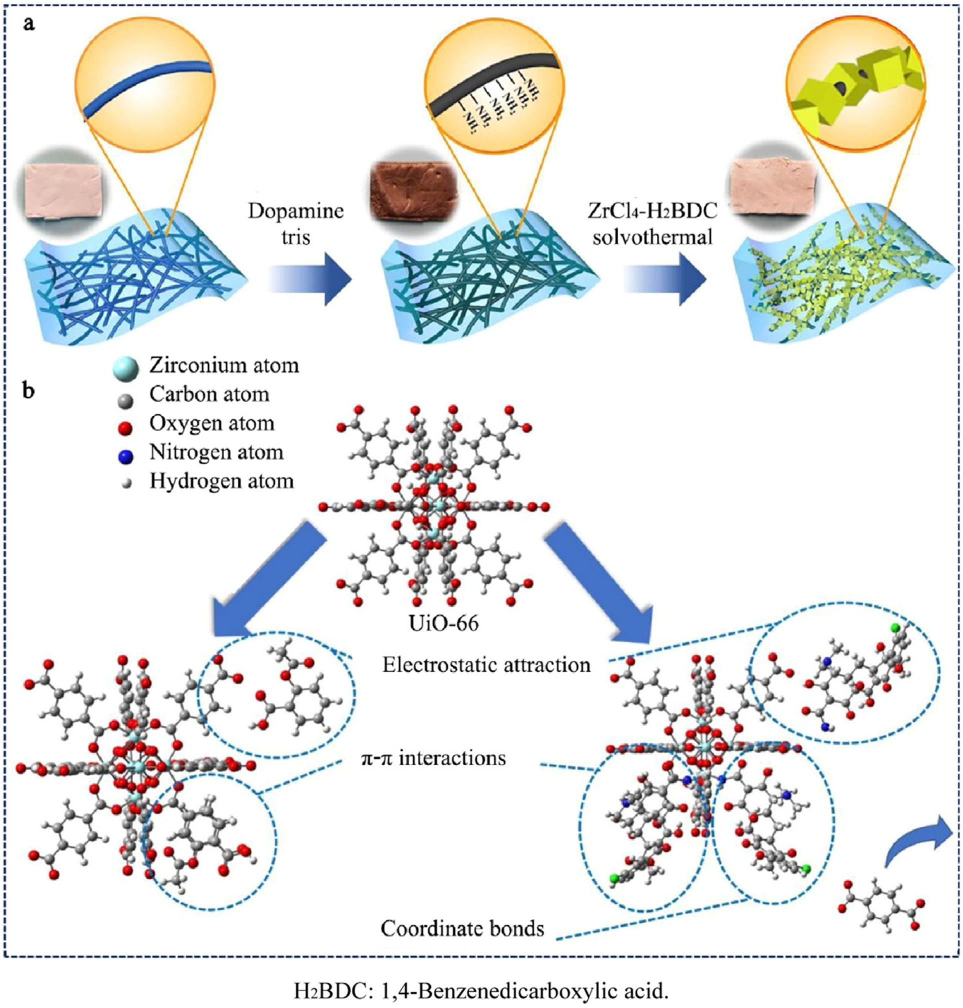


Fig. 18. (a) Synthesis process and (b) adsorption mechanism of UiO-66/polydopamine/bacterial cellulose aerogel (Cui et al., 2020)
H_2BDC: 1,4-Benzenedicarboxylic acid.

decontamination process, they are helpful in the removal of heavy metals, drugs and cosmetics, radionuclides, oil and organic dyes. The advantages of cellulose-based materials for wastewater treatment are given below.

Cellulose is an abundant naturally occurring biopolymer and can be derived from different origins, such as plant biomass and agricultural scrap (Jha and Kumar, 2019). Its availability drives it as a sustainable and renewable alternative for wastewater processing applications. Cellulose-based materials have outstanding adsorption capabilities, permitting them to effectively withdraw a broad range of pollutants from wastewater (Zhu et al., 2023). They can adsorb contaminants such as heavy metals, dyes, organic compounds, and even pathogens, enhancing water quality. As a biodegradable material, cellulose can efficiently split down over time (George and Sabapathi, 2015). This property is helpful in wastewater treatment as it decreases the environmental effect of the utilized materials and assures proper removal after usage.

Cellulose-based materials are usually cost-effective compared to traditional wastewater treatment processes (Kausar et al., 2023). Since cellulose can be acquired from renewable sources, its raw material costs are low. Further, the manufacturing methods for cellulose-based materials are relatively easy and affordable. Cellulose-based materials can be engineered and altered to improve their performance in wastewater processing (Cai et al., 2017). By combining different functional groups or presenting nanoscale structures, the adsorption capability, selectivity, and general efficiency of cellulose-based materials can be enhanced for specific pollutants. The need for alternative harmful chemicals is also reduced by using cellulose-based materials for water treatment. Some common pollutants present in water and their removal process are shown in Fig. 19 (Abdelhamid and Mathew, 2021b).

The main disadvantage of cellulose-based materials is the generation of large amounts of sludge and its poor moisture resistance. These materials also have poor mechanical properties (Jayarathna et al., 2022). The disadvantages of the cellulose-based materials used in wastewater treatment applications are shown below. Cellulose-based materials can have restricted chemical stability in specific circumstances, particularly when exposed to strong acids, bases, or harsh chemical essentials (Kumar et al., 2017). This can lead

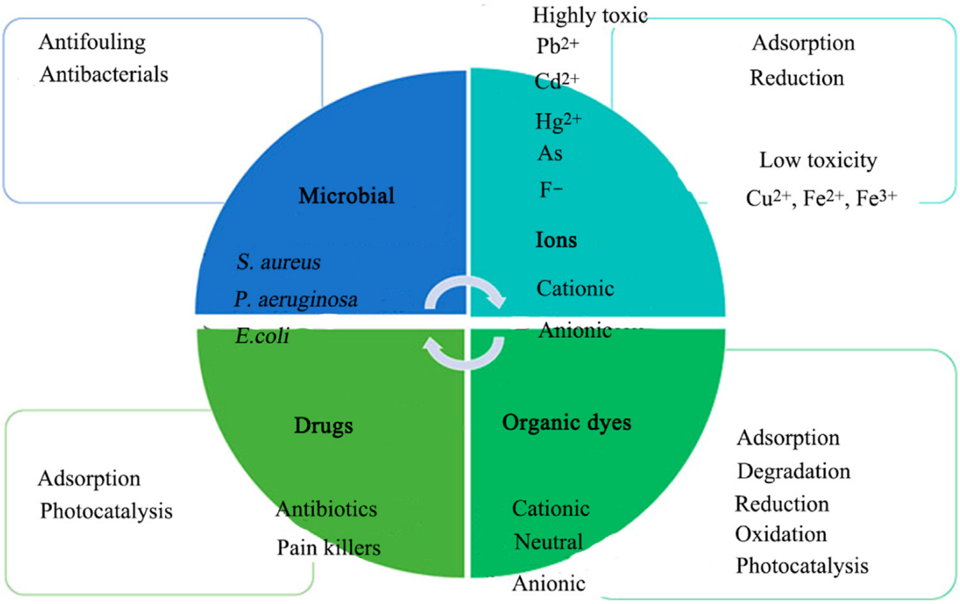


Fig. 19. Some common pollutants in wastewater and their removal process based on cellulose-based materials (Abdelhamid and Mathew, 2021b).

to degradation or decreased performance over time, affecting their efficacy in wastewater treatment. Cellulose-based materials usually contain water which affects their handling and processing (Symington et al., 2009). High water content can raise the materials' weight and bulk, making them challenging to transport and manipulate in large-scale wastewater treatment methods. The adsorption kinetics of cellulose-based materials are slow compared to other adsorbents (Tang et al., 2013). This suggests that extracting pollutants from wastewater may take longer time, needing a longer connection time or more amounts of the material for effective processing. While cellulose-based materials can withdraw a broad range of pollutants, their selectivity for particular pollutants may be determined (Tan et al., 2020). In some circumstances, there may be better choices for targeting specific contaminants. In addition, regeneration of cellulose-based materials after adsorption can be complex. Relying upon the involved specific contaminants and adsorption mechanisms, specialized procedures or additional actions may be required to fully restore the adsorption capability of the material (Ul-Islam et al., 2016).

Consideration of these advantages and disadvantages is essential when considering the appropriateness of cellulose-based materials for wastewater treatment applications. While they suggest considerable advantages, the wastewater's specific requirements and features should be considered to ensure optimal treatment performance.

Economic and environmental considerations

Cellulose has been gaining interest for applications in biomedical (Figueiredo et al., 2018), food (Khan et al., 2018), automobiles (Asadi et al., 2017), electronics (Wang et al., 2017b), personal care (Naderi et al., 2017), and environmental areas(Hamad et al., 2020). Because of their renewability and potential to address environmental challenges, cellulose-based materials have gained much attention for wastewater treatment. This section explores the economic and environmental considerations associated with cellulose-based materials for wastewater treatment. Cost-effectiveness, life cycle analysis, and eco-friendlyness of cellulose-based materials were discussed, highlighting their potential to achieve economic viability and environmental sustainability through their ability and flexibility to be altered or tuned for a specific application (Kim et al., 2018; Muqeet et al., 2020).

Economic considerations

Cost-effectiveness

Being abundantly available and derived from renewable sources, cellulose offers a cost advantage over synthetic materials. The production cost of cellulose-based materials for wastewater treatment can be relatively low, especially when utilizing agricultural waste or recycled cellulose sources (Peng et al., 2020; Williams and Wool, 2000). The potential for cellulose regeneration and reuse further contributes to cost-effectiveness.

Scalability

The scale-up of bio-resource retrieval processes is challenging due to budgetary limitations upon energy and resources. While many chemical routes are available for retrieving useful value products from waste substances, the economics must be sustainable. These limitations are also present in biomass re-utilization (Tiwary et al., 2015; Di Vaio et al., 2023). For example, with the production of CNC from waste biomass, different techniques are already available that work well at the bench scale. In contrast, not all can be scaled up to industrial production. It is thus essential to evaluate the feasibility of any future development by analysis and in practical pilot scale experiments to test if the salient characteristics of the bench scale chemical processes are scalable (Bui et al., 2018). Such investigations expose any emergent difficulties that occur during scale-up. Cellulose extraction processes and material fabrication techniques are well-established, enabling low risk, efficient, and reliable production on a commercial scale (Banerjee et al., 2010; Islam et al., 2017).

Integration with existing infrastructure

Cellulose-based materials can be integrated into existing wastewater treatment infrastructure without significant modifications. This adaptability reduces the capital investment required for implementing cellulose-based solutions, making them economically viable options for upgrading or retrofitting existing treatment systems (Dittenber and GangaRao, 2012).

Environmental consideration

Renewable and biodegradable property

Cellulose-based materials are derived from renewable sources such as wood, agricultural waste, and recycled paper, reducing reliance on non-renewable resources (Escursell et al., 2021). Moreover, cellulose is biodegradable, ensuring that the materials used in wastewater treatment do not contribute to long-term environmental pollution (Farghali et al., 2023).

Reduced energy consumption

The production and use of cellulose-based materials for wastewater treatment typically requires less energy than conventional treatment processes (Mohamed et al., 2017). The lightweight cellulose fibres and membranes reduces energy requirements for transportation, installation, and operation. Additionally, using cellulose-based adsorbents can minimize the need for energy-intensive regeneration processes.

Reduced chemical usage

The inherent properties of cellulose, such as its adsorption capacity and ability to facilitate biological processes, enable the removal of pollutants without excessive chemical dosing (Giachini et al., 2020). This reduces the environmental impact associated with chemical usage and the generation of chemical sludge.

Life cycle analysis

Life cycle analysis (LCA) provides a comprehensive assessment of the environmental impacts associated with cellulose-based materials throughout their entire life cycle, from raw material extraction to end-of-life disposal or recycling (Anastas and Lankey, 2000). LCA indicated that cellulose-based materials for wastewater treatment exhibits lower environmental burdens compared to conventional materials, particularly in terms of greenhouse gas emissions, energy consumption, and waste generation (Tsang et al., 2019).

Cellulose-based sustainable materials have been shown to offer economic advantages and environmental benefits for wastewater treatment applications. Their cost-effectiveness, scalability, compatibility with existing infrastructure, and their renewability and biodegradability contribute to their financial viability (Li et al., 2022). The reduced energy consumption, decreased chemical usage, and favourable environmental performance highlighted by LCA emphasizes the eco-friendly attributes of cellulose-based materials. These considerations make cellulose-based sustainable materials a good choice for achieving economic and ecological sustainability in wastewater treatment.

Conclusions

Cellulose-based sustainable materials have emerged as a promising alternative for wastewater treatment due to their unique properties and sustainability. Cellulose-based materials have shown potential in various applications, such as adsorption, membrane separation, catalysis, and integration with other technologies. For wastewater treatment, cellulose-based materials are very efficient and suitable as they are biodegradable, low in cost, and eco-friendly. The biomass-based materials are versatile as they effectively remove many pollutants, like oil, dye, heavy metals, suspended particulate matter, etc., from contaminated or pollutant water. In addition, these cellulose-based materials have superior characteristics like low-cost, biodegradable, and renewable, making them suitable for treating wastewater. In this review article, we discussed the scope of their use and their conversion into a valuable product in wastewater treatment, mainly focussing on removing dye, oil, heavy metal, turbidity. However, challenges remain to be addressed to achieve practical applications in wastewater treatment, including limited mechanical strength, chemical stability, and low reusability. The main challenges associated with water treatment are scaling up from laboratory to industrial level and cutting the cost of raw resources and industrial preparation. Ongoing research in this field aims to overcome these challenges and advance the utilization of cellulose-based materials for wastewater treatment, leading to sustainable and eco-friendly wastewater treatment technologies. Further research is required to explore novel, innovative biomass-based sustainable materials for multi-functional purposes with some alternative biomass raw materials. Overall, the development of cellulose-based sustainable materials for wastewater treatment has the potential to contribute to the goal of achieving a more sustainable and cleaner environment. The continued research and development in this field will be critical in enhancing the performance and practicality of cellulose-based materials for wastewater treatment, paving the way for a more sustainable future.

Declaration of Competing Interest

There are no conflicts to declare.

Acknowledgements

The authors acknowledge the support from the Department of Chemistry and Research & Development Cell of Maharishi Markandeshwar University, Mullana, Ambala, Haryana, India. Further, SSS would like to acknowledge the financial support provided by the UKRI via Grants No EP/T024607/1. VKT would like to acknowledge the Research support provided by the UKRI via Grant No. EP/T024607/1; and Royal Society via grant number IES\R2\222208.

References

Abdelhamid, H.N., Mathew, A.P., 2021a. Cellulose-based materials for water remediation: adsorption, catalysis, and antifouling. Front. Chem. Eng. 3, 790314.
Abdelhamid, H.N., Mathew, A.P., 2021b. Cellulose-based materials for water remediation: adsorption, catalysis, and antifouling. Front. Chem. Eng. 3, 790314.
Adebajo, M.O., Frost, R.L., Kloprogge, J.T., Carmody, O., Kokot, S., 2003. Porous materials for oil spill cleanup: a review of synthesis and absorbing properties. J. Porous Mater. 10, 159–170.
Agarwal, U.P., Ralph, S.A., Baez, C., Reiner, R.S., Verrill, S.P., 2017. Effect of sample moisture content on XRD-estimated cellulose crystallinity index and crystallite size. Cellulose 24, 1971–1984.
Aguilera, F., Méndez, J., Pásaro, E., Laffon, B., 2010. Review on the effects of exposure to spilled oils on human health. J. Appl. Toxicol. 30, 291–301.
Ahmad, A., 2021. Increase in frequency of nuclear power outages due to changing climate. Nat. Energy 6, 755–762.
Ahmad, M., Wu, F., Cui, Y.H., Zhang, Q.Y., Zhang, B.L., 2020. Preparation of novel bifunctional magnetic tubular nanofibers and their application in efficient and irreversible uranium trap from aqueous solution. ACS Sustainable Chem. Eng. 8, 7825–7838.
Ahmad, M.A., Ahmed, N.B., Adegoke, K.A., Bello, O.S., 2019. Sorption studies of methyl red dye removal using lemon grass (*Cymbopogon citratus*). Chem. Data Collect. 22, 100249.
Akter, M., Bhattacharjee, M., Dhar, A.K., Rahman, F.B.A., Haque, S., Rashid, T.U., Kabir, S.M.F., 2021. Cellulose-based hydrogels for wastewater treatment: a concise review. Gels 7, 30.
Alila, S., Boufi, S., 2009. Removal of organic pollutants from water by modified cellulose fibres. Ind. Crops Prod. 30, 93–104.
Aloulou, F., Boufi, S., Labidi, J., 2006. Modified cellulose fibres for adsorption of organic compound in aqueous solution. Sep. Purif. Technol. 52, 332–342.
Alyüz, B., Veli, S., 2009. Kinetics and equilibrium studies for the removal of nickel and zinc from aqueous solutions by ion exchange resins. J. Hazard. Mater. 167, 482–488.
Anastas, P.T., Lankey, R.L., 2000. Life cycle assessment and green chemistry: the Yin and Yang of industrial ecology. Green Chem. 2, 289–295.
Antal, M., Karhunmaa, K., 2018. The German energy transition in the British, Finnish and Hungarian news media. Nat. Energy 3, 994–1001.
Araki, J., Wada, M., Kuga, S., 2001. Steric stabilization of a cellulose microcrystal suspension by poly(ethylene glycol) grafting. Langmuir 17, 21–27.
Armor, J.N., 1999. The multiple roles for catalysis in the production of H_2. Appl. Catal. A 176, 159–176.
Asadi, A., Miller, M., Singh, A.V., Moon, R.J., Kalaitzidou, K., 2017. Lightweight sheet molding compound (SMC) composites containing cellulose nanocrystals. Compos. Struct. 160, 211–219.
Asadullah, M., Asaduzzaman, M., Kabir, M.S., Mostofa, M.G., Miyazawa, T., 2010. Chemical and structural evaluation of activated carbon prepared from jute sticks for Brilliant Green dye removal from aqueous solution. J. Hazard. Mater. 174, 437–443.
Askari, S., Khodaei, M.M., Jafarzadeh, M., Mikaeili, A., 2022. In-situ formation of Ag NPs on the ribonic γ-lactone-modified UiO-66-NH_2: an effective catalyst for organic synthesis and antibacterial applications. Process. Biochem. 122, 149–165.
Azizi Samir, M.A., Alloin, F., Dufresne, A., 2005. Review of recent research into cellulosic whiskers, their properties and their application in nanocomposite field. Biomacromolecules 6, 612–626.
Bai, Z.H., Liu, Q., Zhang, H.S., Liu, J.Y., Yu, J., Wang, J., 2020. A novel 3D reticular anti-fouling bio-adsorbent for uranium extraction from seawater: polyethylenimine and guanidyl functionalized hemp fibers. Chem. Eng. J. 382, 122555.
Banavath, H.N., Bhardwaj, N.K., Ray, A.K., 2011. A comparative study of the effect of refining on charge of various pulps. Bioresour. Technol. 102, 4544–4551.
Banerjee, S., Mudliar, S., Sen, R., Giri, B., Satpute, D., Chakrabarti, T., Pandey, R.A., 2010. Commercializing lignocellulosic bioethanol: technology bottlenecks and possible remedies. Biofuels Bioprod. Biorefin. 4, 77–93.
Barakat, M.A., 2011. New trends in removing heavy metals from industrial wastewater. Arab. J. Chem. 4, 361–377.
Bhattacharyya, K.G., Sarma, A., 2003. Adsorption characteristics of the dye, Brilliant Green, on Neem leaf powder. Dyes Pigm 57, 211–222.
Bin Bakri, M.K., Rahman, M.R., 2022. Applications of Cellulose Materials and Their composites. Fundamentals and Recent Advances in Nanocomposites Based On Polymers and Nanocellulose. Elsevier, Amsterdam, pp. 267–284.
Brooks, B.W., Lazorchak, J.M., Howard, M.D.A., Johnson, M.V V., Morton, S.L., Perkins, D.A.K., Reavie, E.D., Scott, G.I., Smith, S.A., Steevens, J.A., 2016. Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems? Environ. Toxicol. Chem. 35, 6–13.
Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., Fuss, S., Galindo, A., Hackett, L.A., Hallett, J.P., Herzog, H.J., Jackson, G., Kemper, J., Krevor, S., Maitland, G.C., Matuszewski, M., Metcalfe, I.S., Petit, C., Puxty, G., Reimer, J., Reiner, D.M., Rubin, E.S., Scott, S.A., Shah, N., Smit, B., Martin Trusler, J.P., Webley, P., Wilcox, J., Mac Dowell, N., 2018. Carbon capture and storage (CCS): the way forward. Energy Environ. Sci. 11, 1062–1176.
Cai, J., Kimura, S., Wada, M., Kuga, S., 2009. Nanoporous cellulose as metal nanoparticles support. Biomacromolecules 10, 87–94.
Cai, J., Lei, M., Zhang, Q., He, J.R., Chen, T., Liu, S., Fu, S.H., Li, T.T., Liu, G., Fei, P., 2017. Electrospun composite nanofiber mats of Cellulose@Organically modified montmorillonite for heavy metal ion removal: design, characterization, evaluation of absorption performance. Compos. A 92, 10–16.
Chang, C.Y., Zhang, L.N., 2011. Cellulose-based hydrogels: present status and application prospects. Carbohydr. Polym. 84, 40–53.
Chen, B., Zheng, Q.F., Zhu, J.L., Li, J.H., Cai, Z.Y., Chen, L.G., Gong, S.Q., 2016a. Mechanically strong fully biobased anisotropic cellulose aerogels. RSC Adv. 6, 96518–96526.
Chen, M.J., Zhang, X.Q., Zhang, A.P., Liu, C.F., Sun, R.C., 2016b. Direct preparation of green and renewable aerogel materials from crude bagasse. Cellulose 23, 1325–1334.
Chen, W.J., Su, Y.L., Zheng, L.L., Wang, L.J., Jiang, Z.Y., 2009. The improved oil/water separation performance of cellulose acetate-graft-polyacrylonitrile membranes. J. Membr. Sci. 337, 98–105.
Choi, H.Y., Bae, J.H., Hasegawa, Y., An, S., Kim, I.S., Lee, H., Kim, M., 2020. Thiol-functionalized cellulose nanofiber membranes for the effective adsorption of heavy metal ions in water. Carbohydr. Polym. 234, 115881.
Chowdhury, S., Chakraborty, S., Saha, P., 2011. Biosorption of Basic Green 4 from aqueous solution by *Ananas comosus* (pineapple) leaf powder. Colloids Surf. B Biointerfaces 84, 520–527.
Corsellis, Y.Y., Krasovec, M.M., Sylvi, L.L., Cuny, P.P., Militon, C.C., 2016. Oil removal and effects of spilled oil on active microbial communities in close to salt-saturation brines. Extremophiles 20, 235–250.
Cui, J., Xu, X.R., Yang, L.Y., Chen, C.T., Qian, J.S., Chen, X., Sun, D.P., 2020. Soft foam-like UiO-66/polydopamine/bacterial cellulose composite for the removal of aspirin and tetracycline hydrochloride. Chem. Eng. J. 395, 125174.
da Silva, A.F.V., da Silva, J., Vicente, R., Ambrosi, A., Zin, G., Di Luccio, M., de Oliveira, J.V., 2023. Recent advances in surface modification using polydopamine for the development of photocatalytic membranes for oily wastewater treatment. J. Water Process. Eng. 53, 103743.

Dada, E.O., Ojo, I.A., Alade, A.O., Afolabi, T.J., Jimoh, M.O., Dauda, M.O., 2020. Biosorption of bromo-based dyes from wastewater using low-cost adsorbents: a review. J. Sci. Res. Rep. 34–56.

DeLaune, R.D., Wright, A.L., 2011. Projected impact of deepwater horizon oil spill on U.S. gulf coast wetlands. Soil Sci. Soc. Am. J. 75, 1602–1612.

Deniz, F., Karaman, S., 2011. Removal of Basic Red 46 dye from aqueous solution by pine tree leaves. Chem. Eng. J. 170, 67–74.

Deshwal, N., Singh, M.B., Bahadur, I., Kaushik, N., Kaushik, N.K., Singh, P., Kumari, K., 2023. A review on recent advancements on removal of harmful metal/metal ions using graphene oxide: experimental and theoretical approaches. Sci. Total Environ. 858, 159672.

Dhali, K., Ghasemlou, M., Daver, F., Cass, P., Adhikari, B., 2021. A review of nanocellulose as a new material towards environmental sustainability. Sci. Total Environ. 775, 145871.

Di Vaio, A., Hasan, S., Palladino, R., Hassan, R., 2023. The transition towards circular economy and waste within accounting and accountability models: a systematic literature review and conceptual framework. Environ. Dev. Sustain. 25, 734–810.

Ding, L.L., Zou, B., Gao, W., Liu, Q., Wang, Z.C., Guo, Y.P., Wang, X.F., Liu, Y.H., 2014. Adsorption of Rhodamine-B from aqueous solution using treated rice husk-based activated carbon. Colloids Surf. A 446, 1–7.

Dittenber, D.B., GangaRao, H.V.S., 2012. Critical review of recent publications on use of natural composites in infrastructure. Compos. A 43, 1419–1429.

Domínguez-Robles, J., Peresin, M.S., Tamminen, T., Rodríguez, A., Larrañeta, E., Jääskeläinen, A.S., 2018. Lignin-based hydrogels with super-swelling capacities for dye removal. Int. J. Biol. Macromol. 115, 1249–1259.

Dong, Y.D., Zhang, H., Zhong, G.J., Yao, G., Lai, B., 2021. Cellulose/carbon composites and their applications in water treatment - a review. Chem. Eng. J. 405, 126980.

El Hariri El Nokab, M., Habib, M.H., Alassmy, Y.A., Abduljawad, M.M., Alshamrani, K.M., Sebakhy, K.O., 2022. Solid state NMR a powerful technique for investigating sustainable/renewable cellulose-based materials. Polymers (Basel) 14, 1049.

El-Hag Ali, A., 2012. Removal of heavy metals from model wastewater by using carboxymehyl cellulose/2-acrylamido-2-methyl propane sulfonic acid hydrogels. J. Appl. Polym. Sci. 123, 763–769.

Eqbalpour, M., Andooz, A., Kowsari, E., Ramakrishna, S., Cheshmeh, Z.A., Chinnappan, A., 2023. A comprehensive review on how ionic liquids enhance the pyrolysis of cellulose, lignin, and lignocellulose toward a circular economy. Wiley Interdiscip. Rev. 12, e473.

Escursell, S., Llorach-Massana, P., Roncero, M.B., 2021. Sustainability in e-commerce packaging: a review. J. Clean. Prod. 280, 124314.

Etim, A.O., Musonge, P., Eloka-Eboka, A.C., 2020. Effectiveness of biogenic waste-derived heterogeneous catalysts and feedstock hybridization techniques in biodiesel production. Biofuels Bioprod. Biorefin. 14, 620–649.

Fan, P.D., Yuan, Y.L., Ren, J.K., Yuan, B., He, Q., Xia, G.M., Chen, F.X., Song, R., 2017. Facile and green fabrication of cellulosed based aerogels for lampblack filtration from waste newspaper. Carbohydr. Polym. 162, 108–114.

Fang, Y., Chen, S.F., Luo, X., Wang, C.Y., Yang, R.Z., Zhang, Q.J., Huang, C.Q., Shao, T., 2016. Synthesis and characterization of cellulose triacetate aerogels with ultralow densities. RSC Adv. 6, 54054–54059.

Farghali, M., Mohamed, I.M.A., Osman, A.I., Rooney, D.W., 2023. Seaweed for climate mitigation, wastewater treatment, bioenergy, bioplastic, biochar, food, pharmaceuticals, and cosmetics: a review. Environ. Chem. Lett. 21, 97–152.

Figueiredo, P., Lintinen, K., Hirvonen, J.T., Kostiainen, M.A., Santos, H.A., 2018. Properties and chemical modifications of lignin: towards lignin-based nanomaterials for biomedical applications. Prog. Mater. Sci. 93, 233–269.

Fu, J.J., Wang, S.Q., He, C.X., Lu, Z.X., Huang, J.D., Chen, Z.L., 2016. Facilitated fabrication of high strength silica aerogels using cellulose nanofibrils as scaffold. Carbohydr. Polym. 147, 89–96.

Garvey, C.J., Parker, I.H., Simon, G.P., 2005. On the interpretation of X-ray diffraction powder patterns in terms of the nanostructure of cellulose I fibres. Macromol. Chem. Phys. 206, 1568–1575.

Gavillon, R., Budtova, T., 2008. Aerocellulose: new highly porous cellulose prepared from cellulose-NaOH aqueous solutions. Biomacromolecules 9, 269–277.

George, J., Sabapathi, S.N., 2015. Cellulose nanocrystals: synthesis, functional properties, and applications. Nanotechnol. Sci. Appl. 8, 45–54.

Giachini, P.A.G.S., Gupta, S.S., Wang, W., Wood, D., Yunusa, M., Baharlou, E., Sitti, M., Menges, A., 2020. Additive manufacturing of cellulose-based materials with continuous, multidirectional stiffness gradients. Sci. Adv. 6, eaay0929.

Granata, A., Argyropoulos, D.S., 1995. 2-chloro-4,4,5,5-tetramethyl-1,3,2-dioxaphospholane, a reagent for the accurate determination of the uncondensed and condensed phenolic moieties in lignins. J. Agric. Food Chem. 43, 1538–1544.

Habibi, Y., 2014. Key advances in the chemical modification of nanocelluloses. Chem. Soc. Rev. 43, 1519–1542.

Hamad, A.A., Hassouna, M.S., Shalaby, T.I., Elkady, M.F., Abd Elkawi, M.A., Hamad, H.A., 2020. Electrospun cellulose acetate nanofiber incorporated with hydroxyapatite for removal of heavy metals. Int. J. Biol. Macromol. 151, 1299–1313.

Hameed, B.H., 2009a. Grass waste: a novel sorbent for the removal of basic dye from aqueous solution. J. Hazard. Mater. 166, 233–238.

Hameed, B.H., 2009b. Removal of cationic dye from aqueous solution using jackfruit peel as non-conventional low-cost adsorbent. J. Hazard. Mater. 162, 344–350.

Hameed, B.H., Ahmad, A.A., 2009. Batch adsorption of methylene blue from aqueous solution by garlic peel, an agricultural waste biomass. J. Hazard. Mater. 164, 870–875.

Heath, L., Thielemans, W., 2010. Cellulose nanowhisker aerogels. Green Chem. 12, 1448–1453.

Hernández-Delgado, E.A., 2015. The emerging threats of climate change on tropical coastal ecosystem services, public health, local economies and livelihood sustainability of small islands: cumulative impacts and synergies. Mar. Pollut. Bull. 101, 5–28.

Herrera-Morales, J., Morales, K., Ramos, D., Ortiz-Quiles, E.O., López-Encarnación, J.M., Nicolau, E., 2017. Examining the use of nanocellulose composites for the sorption of contaminants of emerging concern: an experimental and computational study. ACS Omega 2, 7714–7722.

Hoepfner, S., Ratke, L., Milow, B., 2008. Synthesis and characterisation of nanofibrillar cellulose aerogels. Cellulose 15, 121–129.

Hokkanen, S., Bhatnagar, A., Repo, E., Lou, S., Sillanpää, M., 2016. Calcium hydroxyapatite microfibrillated cellulose composite as a potential adsorbent for the removal of Cr(VI) from aqueous solution. Chem. Eng. J. 283, 445–452.

Islam, M.S., Kao, N., Bhattacharya, S.N., Gupta, R., Bhattacharjee, P.K., 2017. Effect of low pressure alkaline delignification process on the production of nanocrystalline cellulose from rice husk. J. Taiwan Inst. Chem. Engineers 80, 820–834.

Isobe, N., Chen, X.X., Kim, U.J., Kimura, S., Wada, M., Saito, T., Isogai, A., 2013. TEMPO-oxidized cellulose hydrogel as a high-capacity and reusable heavy metal ion adsorbent. J. Hazard. Mater. 260, 195–201.

Jalvo, B., Aguilar-Sanchez, A., Ruiz-Caldas, M.X., Mathew, A.P., 2021. Water filtration membranes based on non-woven cellulose fabrics: effect of nanopolysaccharide coatings on selective particle rejection, antifouling, and antibacterial properties. Nanomaterials 11, 1752.

Jamshaid, A., Hamid, A., Muhammad, N., Naseer, A., Ghauri, M., Iqbal, J., Rafiq, S., Shah, N.S., 2017. Cellulose-based materials for the removal of heavy metals from wastewater - an overview. ChemBioEng Rev. 4, 240–256.

Jawad, A.H., Rashid, R.A., Ishak, M.A.M., Wilson, L.D., 2016. Adsorption of methylene blue onto activated carbon developed from biomass waste by H_2SO_4 activation: kinetic, equilibrium and thermodynamic studies. Desalin. Water Treat. 57, 25194–25206.

Jayarathna, S., Andersson, M., Andersson, R., 2022. Recent advances in starch-based blends and composites for bioplastics applications. Polymers (Basel) 14, 4557.

Jha, A., Kumar, A., 2019. Biobased technologies for the efficient extraction of biopolymers from waste biomass. Bioprocess Biosyst. Eng. 42, 1893–1901.

Ji, F., Li, C.L., Tang, B., Xu, J.H., Lu, G., Liu, P., 2012. Preparation of cellulose acetate/zeolite composite fiber and its adsorption behavior for heavy metal ions in aqueous solution. Chem. Eng. J. 209, 325–333.

Jiang, F., Hsieh, Y.L., 2014. Super water absorbing and shape memory nanocellulose aerogels from TEMPO-oxidized cellulose nanofibrils *via* cyclic freezing-thawing. J. Mater. Chem. A 2, 350–359.

Kabir, S.M.F., Sikdar, P.P., Haque, B., Bhuiyan, M.A.R., Ali, A., Islam, M.N., 2018. Cellulose-based hydrogel materials: chemistry, properties and their prospective applications. Prog. Biomater. 7, 153–174.

Karadagli, I., Schulz, B., Schestakow, M., Milow, B., Gries, T., Ratke, L., 2015. Production of porous cellulose aerogel fibers by an extrusion process. J. Supercrit. Fluids 106, 105–114.

Karnitz Jr, O., Gurgel, L.V.A., de Melo, J.C.P., Botaro, V.R., Melo, T.M.S., de Freitas Gil, R.P., Gil, L.F., 2007. Adsorption of heavy metal ion from aqueous single metal solution by chemically modified sugarcane bagasse. Bioresour. Technol. 98, 1291–1297.

Kasaeian, A., Javidmehr, M., Mirzaie, M.R., Fereidooni, L., 2023. Integration of solid oxide fuel cells with solar energy systems: a review. Appl. Therm. Eng. 224, 120117.

Kaur, H., Devi, N., Siwal, S.S., Alsanie, W.F., Thakur, M.K., Thakur, V.K., 2023a. Metal-organic framework-based materials for wastewater treatment: superior adsorbent materials for the removal of hazardous pollutants. ACS Omega 8, 9004–9030.

Kaur, H., Siwal, S.S., Kumar, V., Thakur, V.K., 2023b. Deep eutectic solvents toward the detection and extraction of neurotransmitters: an emerging paradigm for biomedical applications. Ind. Eng. Chem. Res..

Kausar, A., Zohra, S.T., Ijaz, S., Iqbal, M., Iqbal, J., Bibi, I., Nouren, S., El Messaoudi, N., Nazir, A., 2023. Cellulose-based materials and their adsorptive removal efficiency for dyes: a review. Int. J. Biol. Macromol. 224, 1337–1355.

Khan, A., Wen, Y.B., Huq, T., Ni, Y.H., 2018. Cellulosic nanomaterials in food and nutraceutical applications: a review. J. Agric. Food Chem. 66, 8–19.

Kim, C.H., Youn, H.J., Lee, H.L., 2015. Preparation of cross-linked cellulose nanofibril aerogel with water absorbency and shape recovery. Cellulose 22, 3715–3724.

Kim, D.Y., Kadam, A., Shinde, S., Saratale, R.G., Patra, J., Ghodake, G., 2018. Recent developments in nanotechnology transforming the agricultural sector: a transition replete with opportunities. J. Sci. Food Agric. 98, 849–864.

Kim, S.H., Lee, C.M., Kafle, K., 2013. Characterization of crystalline cellulose in biomass: basic principles, applications, and limitations of XRD, NMR, IR, Raman, and SFG. Korean J. Chem. Eng. 30, 2127–2141.

Kishor, R., Purchase, D., Saratale, G.D., Saratale, R.G., Ferreira, L.F.R., Bilal, M., Chandra, R., Bharagava, R.N., 2021. Ecotoxicological and health concerns of persistent coloring pollutants of textile industry wastewater and treatment approaches for environmental safety. J. Environ. Chem. Eng. 9, 105012.

Kistler, S.S., 1931. Coherent expanded aerogels and jellies. Nature 127, 741.

Kistler, S.S., 1932. Coherent expanded aerogels. Rubber Chemistry and Technology 5, 600–603.

Kong, L.J., Ruan, Y., Zheng, Q.Y., Su, M.H., Diao, Z.H., Chen, D.Y., Hou, L.A., Chang, X.Y., Shih, K., 2020. Uranium extraction using hydroxyapatite recovered from phosphorus containing wastewater. J. Hazard. Mater. 382, 120784.

Krishna Kumar, A.S., Kalidhasan, S., Rajesh, V., Rajesh, N., 2013. Adsorptive demercuration by virtue of an appealing interaction involving biopolymer cellulose and mercaptobenzothiazole. Ind. Eng. Chem. Res. 52, 11838–11849.

Ku, Y., Jung, I.L., 2001. Photocatalytic reduction of Cr(VI) in aqueous solutions by UV irradiation with the presence of titanium dioxide. Water Res 35, 135–142.

Kumar, A.S.K., Kalidhasan, S., Rajesh, V., Rajesh, N., 2012. Application of cellulose-clay composite biosorbent toward the effective adsorption and removal of chromium from industrial wastewater. Ind. Eng. Chem. Res. 51, 58–69.

Kumar, R., Sharma, R.K., Singh, A.P., 2017. Cellulose based grafted biosorbents - Journey from lignocellulose biomass to toxic metal ions sorption applications - A review. J. Mol. Liq. 232, 62–93.

Kumari, S., Chauhan, G.S., Ahn, J.H., 2016. Novel cellulose nanowhiskers-based polyurethane foam for rapid and persistent removal of methylene blue from its aqueous solutions. Chem. Eng. J. 304, 728–736.

Lam, S.S., Liew, R.K., Wong, Y.M., Yek, P.N.Y., Ma, N.L., Lee, C.L., Chase, H.A., 2017. Microwave-assisted pyrolysis with chemical activation, an innovative method to convert orange peel into activated carbon with improved properties as dye adsorbent. J. Clean. Prod. 162, 1376–1387.

Landaburu-Aguirre, J., García, V., Pongrácz, E., Keiski, R.L., 2009. The removal of zinc from synthetic wastewaters by micellar-enhanced ultrafiltration: statistical design of experiments. Desalination 240, 262–269.

Lee, J., Kim, S., You, S.M., Park, Y.K., 2023. Bioenergy generation from thermochemical conversion of lignocellulosic biomass-based integrated renewable energy systems. Renew. Sustain. Energy Rev. 178, 113240.

Li, D., Zhu, F.Z., Li, J.Y., Na, P., Wang, N., 2013. Preparation and characterization of cellulose fibers from corn straw as natural oil sorbents. Ind. Eng. Chem. Res. 52, 516–524.

Li, J., Wang, X.X., Zhao, G.X., Chen, C.L., Chai, Z.F., Alsaedi, A., Hayat, T., Wang, X.K., 2018a. Metal-organic framework-based materials: superior adsorbents for the capture of toxic and radioactive metal ions. Chem. Soc. Rev. 47, 2322–2356.

Li, M., Jiang, H.Y., Xu, D., Yang, Y.T., 2017. A facile method to prepare cellulose whiskers-silica aerogel composites. J. Sol Gel Sci. Technol. 83, 72–80.

Li, N., Bai, R.B., 2005. Copper adsorption on chitosan-cellulose hydrogel beads: behaviors and mechanisms. Sep. Purif. Technol. 42, 237–247.

Li, S., Wang, X., Guo, Y.Y., Hu, J.W., Lin, S.D., Tu, Y.Y., Chen, L.H., Ni, Y.H., Huang, L.L., 2022. Recent advances on cellulose-based nanofiltration membranes and their applications in drinking water purification: a review. J. Clean. Prod. 333, 130171.

Li, Y.X., Cao, L.X., Li, L., Yang, C.F., 2015. In situ growing directional spindle TiO_2 nanocrystals on cellulose fibers for enhanced Pb^{2+} adsorption from water. J. Hazard. Mater. 289, 140–148.

Li, Y.X., Li, L., Cao, L.X., Yang, C.F., 2016. Promoting dynamic adsorption of Pb^{2+} in a single pass flow using fibrous nano-TiO_2/cellulose membranes. Chem. Eng. J. 283, 1145–1153.

Li, Y.Y., Wang, B., Ma, M.G., Wang, B., 2018b. Review of recent development on preparation, properties, and applications of cellulose-based functional materials. Int. J. Polym. Sci. 1–18 2018.

Liang, M., Zhang, G., Feng, Y.J., Li, R.L., Hou, P., Zhang, J.S., Wang, J.M., 2018. Facile synthesis of silver nanoparticles on amino-modified cellulose paper and their catalytic properties. J. Mater. Sci. 53, 1568–1579.

Liao, Y.T., Matsagar, B.M., Wu, K.C.W., 2018. Metal–organic framework (MOF)-derived effective solid catalysts for valorization of lignocellulosic biomass. ACS Sustainable Chem. Eng. 6, 13628–13643.

Liebner, F., Haimer, E., Wendland, M., Neouze, M.A., Schlufter, K., Miethe, P., Heinze, T., Potthast, A., Rosenau, T., 2010. Aerogels from unaltered bacterial cellulose: application of $scCO_2$ drying for the preparation of shaped, ultra-lightweight cellulosic aerogels. Macromol. Biosci. 10, 349–352.

Liimatainen, H., Sirviö, J., Sundman, O., Visanko, M., Hormi, O., Niinimäki, J., 2011. Flocculation performance of a cationic biopolymer derived from a cellulosic source in mild aqueous solution. Bioresour. Technol. 102, 9626–9632.

Liu, J., Chen, T.W., Yang, Y.L., Bai, Z.C., Xia, L.R., Wang, M., Lv, X.L., Li, L., 2020. Removal of heavy metal ions and anionic dyes from aqueous solutions using amide-functionalized cellulose-based adsorbents. Carbohydr. Polym. 230, 115619.

Liu, L., Gao, Z.Y., Su, X.P., Chen, X., Jiang, L., Yao, J.M., 2015. Adsorption removal of dyes from single and binary solutions using a cellulose-based bioadsorbent. ACS Sustainable Chem. Eng. 3, 432–442.

Liu, S.C., Wu, M.B., Ye, H., Liu, L., Ma, L.L., Yao, J.M., 2021. Amidoximated cellulose microspheres synthesized via homogenous reactions for High-Performance extraction of uranium from seawater. Chem. Eng. J. 426, 131378.

Long, L.Y., Weng, Y.X., Wang, Y.Z., 2018. Cellulose aerogels: synthesis, applications, and prospects. Polymers (Basel) 10, 623.

Luo, W., Xiao, G., Tian, F., Richardson, J.J., Wang, Y.P., Zhou, J.F., Guo, J.L., Liao, X.P., Shi, B., 2019. Engineering robust metal-phenolic network membranes for uranium extraction from seawater. Energy Environ. Sci. 12, 607–614.

Ma, H.Y., Hsiao, B.S., Chu, B., 2012. Ultrafine cellulose nanofibers as efficient adsorbents for removal of $UO_2{}^{2+}$ in water. ACS Macro Lett. 1, 213–216.

Madaeni, S.S., Gheshlaghi, A., Rekabdar, F., 2013. Membrane treatment of oily wastewater from refinery processes. Asia Pac. J. Chem. Eng. 8, 45–53.

Mahdavinia, G.R., Hasanpour, J., Rahmani, Z., Karami, S., Etemadi, H., 2013. Nanocomposite hydrogel from grafting of acrylamide onto HPMC using sodium montmorillonite nanoclay and removal of crystal violet dye. Cellulose 20, 2591–2604.

Mahmoodi, Y., Mehrnejad, F., Khanmohammadi, S., Shahriari, M., Rahimi, F., Vakili, M.R., Lavasanifar, A., 2022. Molecular insights into the crystalline nanocellulose and human lysozyme interactions: an experimental and theoretical research. Int. J. Biol. Macromol. 213, 83–95.

Maity, J., Ray, S.K., 2017. Removal of Cu (II) ion from water using sugar cane bagasse cellulose and gelatin based composite hydrogels. Int. J. Biol. Macromol. 97, 238–248.

Manos, M.J., Kanatzidis, M.G., 2012. Layered metal sulfides capture uranium from seawater. J. Am. Chem. Soc. 134, 16441–16446.

Mishra, K., Devi, N., Siwal, S.S., Gupta, V.K., Thakur, V.K., 2023a. Hybrid semiconductor photocatalyst nanomaterials for energy and environmental applications: fundamentals, designing, and prospects. Adv. Sustainable Syst. 7, 2300095.

Mishra, K., Devi, N., Siwal, S.S., Thakur, V.K., 2023b. Insight perspective on the synthesis and morphological role of the noble and non-noble metal-based electrocatalyst in fuel cell application. Appl. Catal. B 334, 122820.

Mishra, K., Siwal, S.S., Nayaka, S.C., Guan, Z.W., Thakur, V.K., 2023c. Waste-to-chemicals: green solutions for bioeconomy markets. Sci. Total Environ. 887, 164006.

Missoum, K., Belgacem, M., Bras, J., 2013. Nanofibrillated cellulose surface modification: a review. Materials (Basel) 6, 1745–1766.

Mohamed, M.A., Abd Mutalib, M., Mohd Hir, Z.A., M Zain, M.F., Mohamad, A.B., Jeffery Minggu, L., Awang, N.A., W Salleh, W.N., 2017. An overview on cellulose-based material in tailoring bio-hybrid nanostructured photocatalysts for water treatment and renewable energy applications. Int. J. Biol. Macromol. 103, 1232–1256.

Mohamed, R.R., Seoudi, R.S., Sabaa, M.W., 2012. Synthesis and characterization of antibacterial semi-interpenetrating carboxymethyl chitosan/poly (acrylonitrile) hydrogels. Cellulose 19, 947–958.

Mohanpuria, P., Rana, N.K., Yadav, S.K., 2008. Biosynthesis of nanoparticles: technological concepts and future applications. J. Nanopart. Res. 10, 507–517.

Mohsen-Nia, M., Montazeri, P., Modarress, H., 2007. Removal of Cu^{2+} and Ni^{2+} from wastewater with a chelating agent and reverse osmosis processes. Desalination 217, 276–281.

Moon, R.J., Martini, A., Nairn, J., Simonsen, J., Youngblood, J., 2011. Cellulose nanomaterials review: structure, properties and nanocomposites. Chem. Soc. Rev. 40, 3941–3994.

Moradeeya, P.G., Kumar, M.A., Thorat, R.B., Rathod, M., Khambhaty, Y., Basha, S., 2017. Nanocellulose for biosorption of chlorpyrifos from water: chemometric optimization, kinetics and equilibrium. Cellulose 24, 1319–1332.

Motloung, M.T., Magagula, S.I., Kaleni, A., Sikhosana, T.S., Lebelo, K., Mochane, M.J., 2023. Recent advances on chemically functionalized cellulose-based materials for arsenic removal in wastewater: a review. Water (Basel) 15, 793.

Mujtaba, M., Fernandes Fraceto, L., Fazeli, M., Mukherjee, S., Savassa, S.M., Araujo de Medeiros, G., do Espírito Santo Pereira, A., Mancini, S.D., Lipponen, J., Vilaplana, F., 2023. Lignocellulosic biomass from agricultural waste to the circular economy: *a review with focus on biofuels, biocomposites and bioplastics*. J. Clean. Prod. 402, 136815.

Mülhaupt, R., 2013. Green polymer chemistry and bio-based plastics: dreams and reality. Macromol. Chem. Phys. 214, 159–174.

Mulyadi, A., Zhang, Z., Deng, Y.L., 2016. Fluorine-free oil absorbents made from cellulose nanofibril aerogels. ACS Appl. Mater. Interfaces 8, 2732–2740.

Munirasu, S., Abu Haija, M., Banat, F., 2016. Use of membrane technology for oil field and refinery produced water treatment—a review. Process. Saf. Environ. Prot. 100, 183–202.

Muqeet, M., Mahar, R.B., Gadhi, T.A., Ben Halima, N., 2020. Insight into cellulose-based-nanomaterials - a pursuit of environmental remedies. Int. J. Biol. Macromol. 163, 1480–1486.

Mussatto, S.I., Dragone, G.M., 2016. Biomass pretreatment, biorefineries, and potential products for a bioeconomy development. In: Biomass Fractionation Technologies For a Lignocellulosic Feedstock Based Biorefinery. Elsevier, Amsterdam, pp. 1–22.

Mututuvari, T.M., Tran, C.D., 2014. Synergistic adsorption of heavy metal ions and organic pollutants by supramolecular polysaccharide composite materials from cellulose, chitosan and crown ether. J. Hazard. Mater. 264, 449–459.

Naderi, A., Koschella, A., Heinze, T., Shih, K.C., Nieh, M.P., Pfeifer, A., Chang, C.C., Erlandsson, J., 2017. Sulfoethylated nanofibrillated cellulose: production and properties. Carbohydr. Polym. 169, 515–523.

Nagendran, A., Vijayalakshmi, A., Arockiasamy, D.L., Shobana, K.H., Mohan, D., 2008. Toxic metal ion separation by cellulose acetate/sulfonated poly(ether imide) blend membranes: effect of polymer composition and additive. J. Hazard. Mater. 155, 477–485.

Nasrollahzadeh, M., Ghasemzadeh, M., Gharoubi, H., Nezafat, Z., 2021. Progresses in polysaccharide and lignin-based ionic liquids: catalytic applications and environmental remediation. J. Mol. Liq. 342, 117559.

Nataraj, S.K., Hosamani, K.M., Aminabhavi, T.M., 2007. Potential application of an electrodialysis pilot plant containing ion-exchange membranes in chromium removal. Desalination 217, 181–190.

Nawaz, S., Tabassum, A., Muslim, S., Nasreen, T., Baradoke, A., Kim, T.H., Boczkaj, G., Jesionowski, T., Bilal, M., 2023. Effective assessment of biopolymer-based multifunctional sorbents for the remediation of environmentally hazardous contaminants from aqueous solutions. Chemosphere 329, 138552.

Nguyen, S.T., Feng, J.D., Le, N.T., Le, A.T.T., Hoang, N., Tan, V.B.C., Duong, H.M., 2013. Cellulose aerogel from paper waste for crude oil spill cleaning. Ind. Eng. Chem. Res. 52, 18386–18391.

Ojedokun, A.T., Bello, O.S., 2017. Kinetic modeling of liquid-phase adsorption of Congo red dye using guava leaf-based activated carbon. Appl. Water Sci. 7, 1965–1977.

Oyewo, O.A., Onyango, M.S., Wolkersdorfer, C., 2016. Application of banana peels nanosorbent for the removal of radioactive minerals from real mine water. J. Environ. Radioact. 164, 369–376.

Park, H.G., Kim, T.W., Chae, M.Y., Yoo, I.K., 2007. Activated carbon-containing alginate adsorbent for the simultaneous removal of heavy metals and toxic organics. Process. Biochem. 42, 1371–1377.

Pathak, V.M., Navneet, 2017. Review on the current status of polymer degradation: a microbial approach. Bioresour. Bioprocess. 4, 1–31.

Pei, A.H., Butchosa, N., Berglund, L.A., Zhou, Q., 2013. Surface quaternized cellulose nanofibrils with high water absorbency and adsorption capacity for anionic dyes. Soft Matter 9, 2047–2055.

Peng, B.L., Yao, Z.L., Wang, X.C., Crombeen, M., Sweeney, D.G., Tam, K.C., 2020. Cellulose-based materials in wastewater treatment of petroleum industry. Green Energy Environ 5, 37–49.

Peydayesh, M., Rahbar-Kelishami, A., 2015. Adsorption of methylene blue onto *Platanus orientalis* leaf powder: kinetic, equilibrium and thermodynamic studies. J. Ind. Eng. Chem. 21, 1014–1019.

Pillai, S.S., Deepa, B., Abraham, E., Girija, N., Geetha, P., Jacob, L., Koshy, M., 2013. Biosorption of Cd(II) from aqueous solution using xanthated nano banana cellulose: equilibrium and kinetic studies. Ecotoxicol. Environ. Saf. 98, 352–360.

Pircher, N., Carbajal, L., Schimper, C., Bacher, M., Rennhofer, H., Nedelec, J.M., Lichtenegger, H.C., Rosenau, T., Liebner, F., 2016. Impact of selected solvent systems on the pore and solid structure of cellulose aerogels. Cellulose 23, 1949–1966.

Pranata Putra, W., Kamari, A., Najiah Mohd Yusoff, S., Fauziah Ishak, C., Mohamed, A., Hashim, N., Md Isa, I., 2014. Biosorption of Cu(II), Pb(II) and Zn(II) ions from aqueous solutions using selected waste materials: adsorption and characterisation studies. J. Encapsulation Adsorpt. Sci. 4, 25–35.

Qin, R.C., Ma, Y.Y., Wang, D., Bao, N.Z., Liu, C.G., 2023. Preparation of cellulose nanofibers from corn stalks by Fenton reaction: a new insight into the mechanism by an experimental and theoretical study. J. Agric. Food Chem. 71, 1907–1920.

Qiu, B., Guo, J., Zhang, X., Sun, D.Z., Gu, H.B., Wang, Q., Wang, H.W., Wang, X.F., Zhang, X., Weeks, B.L., Guo, Z.H., Wei, S.Y., 2014. Polyethylenimine facilitated ethyl cellulose for hexavalent chromium removal with a wide pH range. ACS Appl. Mater. Interfaces 6, 19816–19824.

Rajinipriya, M., Nagalakshmaiah, M., Robert, M., Elkoun, S., 2018. Importance of agricultural and industrial waste in the field of nanocellulose and recent industrial developments of wood based nanocellulose: a review. ACS Sustainable Chem. Eng. 6, 2807–2828.

Ramezanzadeh, M., Bahlakeh, G., Sanaei, Z., Ramezanzadeh, B., 2018. Studying the *Urtica dioica* leaves extract inhibition effect on the mild steel corrosion in 1M HCl solution: complementary experimental, *ab initio* quantum mechanics, Monte Carlo and molecular dynamics studies. J. Mol. Liq. 272, 120–136.

Rana, A.K., Guleria, S., Gupta, V.K., Thakur, V.K., 2023a. Cellulosic pine needles-based biorefinery for a circular bioeconomy. Bioresour. Technol. 367, 128255.

Rana, A.K., Mostafavi, E., Alsanie, W.F., Siwal, S.S., Thakur, V.K., 2023b. Cellulose-based materials for air purification: a review. Ind. Crops Prod. 194, 116331.

Raucci, M.G., Alvarez-Perez, M.A., Demitri, C., Giugliano, D., De Benedictis, V., Sannino, A., Ambrosio, L., 2015. Effect of citric acid crosslinking cellulose-based hydrogels on osteogenic differentiation. J. Biomed. Mater. Res. A 103, 2045–2056.

Rethinasabapathy, M., Kang, S.M., Lee, I., Lee, G.W., Hwang, S.K., Roh, C., Huh, Y.S., 2018. Layer-structured POSS-modified Fe-aminoclay/carboxymethyl cellulose composite as a superior adsorbent for the removal of radioactive cesium and cationic dyes. Ind. Eng. Chem. Res. 57, 13731–13741.

Ribul, M., Lanot, A., Tommencioni Pisapia, C., Purnell, P., McQueen-Mason, S.J., Baurley, S., 2021. Mechanical, chemical, biological: moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles. J. Clean. Prod. 326, 129325.

Rocky, M.M.H., Rahman, I.M.M., Biswas, F.B., Rahman, S., Endo, M., Wong, K.H., Mashio, A.S., Hasegawa, H., 2023. Cellulose-based materials for scavenging toxic and precious metals from water and wastewater: a review. Chem. Eng. J. 472, 144677.

Sadrzadeh, M., Mohammadi, T., Ivakpour, J., Kasiri, N., 2009. Neural network modeling of Pb^{2+} removal from wastewater using electrodialysis. Chem. Eng. Process. 48, 1371–1381.

Sai, H.Z., Xing, L., Xiang, J.H., Cui, L.J., Jiao, J.B., Zhao, C.L., Li, Z.Y., Li, F., Zhang, T., 2014. Flexible aerogels with interpenetrating network structure of bacterial cellulose-silica composite from sodium silicate precursor *via* freeze drying process. RSC Adv 4, 30453–30461.

Sajid, M., Nazal, M.K., Baig, N., Osman, A.M., 2018. Removal of heavy metals and organic pollutants from water using dendritic polymers based adsorbents: a critical review. Sep. Purif. Technol. 191, 400–423.

Santoso, S.P., Kurniawan, A., Soetaredjo, F.E., Cheng, K.C., Putro, J.N., Ismadji, S., Ju, Y.H., 2019. Eco-friendly cellulose-bentonite porous composite hydrogels for adsorptive removal of azo dye and soilless culture. Cellulose 26, 3339–3358.

Sanyang, M.L., Sapuan, S.M., Jawaid, M., Ishak, M.R., Sahari, J., 2016. Recent developments in sugar palm (*Arenga pinnata*) based biocomposites and their potential industrial applications: a review. Renew. Sustain. Energy Rev. 54, 533–549.

Satari, B., Karimi, K., Kumar, R., 2019. Cellulose solvent-based pretreatment for enhanced second-generation biofuel production: a review. Sustainable Energy Fuels 3, 11–62.

Sayyed, A.J., Pinjari, D.V., Sonawane, S.H., Bhanvase, B.A., Sheikh, J., Sillanpää, M., 2021. Cellulose-based nanomaterials for water and wastewater treatments: a review. J. Environ. Chem. Eng. 9, 106626.

Schenzel, K., Almlöf, H., Germgård, U., 2009. Quantitative analysis of the transformation process of cellulose I → cellulose II using NIR FT Raman spectroscopy and chemometric methods. Cellulose 16, 407–415.

Schröfel, A., Kratošová, G., Šafařík, I., Šafaříková, M., Raška, I., Shor, L.M., 2014. Applications of biosynthesized metallic nanoparticles - a review. Acta Biomater 10, 4023–4042.

Sehaqui, H., Mautner, A., Perez de Larraya, U., Pfenninger, N., Tingaut, P., Zimmermann, T., 2016. Cationic cellulose nanofibers from waste pulp residues and their nitrate, fluoride, sulphate and phosphate adsorption properties. Carbohydr. Polym. 135, 334–340.

Septevani, A.A., Rifathin, A., Sari, A.A., Sampora, Y., Ariani, G.N., Sudiyarmanto, Sondari D., 2020. Oil palm empty fruit bunch-based nanocellulose as a super-adsorbent for water remediation. Carbohydr. Polym. 229, 115433.

Shahalam, A.M., Al-Harthy, A., Al-Zawhry, A., 2002. Feed water pretreatment in RO systems: unit processes in the middle east. Desalination 150, 235–245.

Shao, Y.Z., Luo, B., Liu, T., Cai, C.C., Meng, X.J., Wang, S.F., Nie, S.X., 2023. Harvesting energy from extreme environmental conditions with cellulosic triboelectric materials. Mater. Today 66, 348–370.

Sharma, G., Kumar, A., Sharma, S., Naushad, M., Ghfar, A.A., Al-Muhtaseb, A.H., Ahamad, T., Sharma, N., Stadler, F.J., 2020. Carboxymethyl cellulose structured nano-adsorbent for removal of methyl violet from aqueous solution: isotherm and kinetic analyses. Cellulose 27, 3677–3691.

Sharma, S., Asolekar, S.R., Thakur, V.K., Asokan, P., 2023. Valorization of cellulosic fiber derived from waste biomass of constructed wetland as a potential reinforcement in polymeric composites: a technological approach to achieve circular economy. J. Environ. Manage. 340, 117850.

Shen, K., Gondal, M.A., 2017. Removal of hazardous Rhodamine dye from water by adsorption onto exhausted coffee ground. J. Saudi Chem. Soc. 21, S120–S127.

Shen, R.J., Xue, S.W., Xu, Y.R., Liu, Q., Feng, Z., Ren, H., Zhai, H.M., Kong, F.G., 2020. Research progress and development demand of nanocellulose reinforced polymer composites. Polymers (Basel) 12, 2113.

Sheoran, K., Kaur, H., Siwal, S.S., Saini, A.K., Vo, D.V N., Thakur, V.K., 2022. Recent advances of carbon-based nanomaterials (CBNMs) for wastewater treatment: synthesis and application. Chemosphere 299, 134364.

Sheoran, K., Kaur, H., Siwal, S.S., Thakur, V.K., 2023. Dual role is always better than single: ionic liquid as a reaction media and electrolyte for carbon-based materials in supercapacitor applications. Adv. Energy Sustain. Res. 4, 2300021.

Shi, Y.R., Xue, Z.H., Wang, X.M., Wang, L., Wang, A.Q., 2013. Removal of methylene blue from aqueous solution by sorption on lignocellulose-*g*-poly(acrylic acid)/montmorillonite three-dimensional cross-linked polymeric network hydrogels. Polym. Bull. 70, 1163–1179.

Siddiqui, S.I., Manzoor, O., Mohsin, M., Chaudhry, S.A., 2019. *Nigella sativa* seed based nanocomposite-MnO_2/BC: an antibacterial material for photocatalytic degradation, and adsorptive removal of Methylene blue from water. Environ. Res. 171, 328–340.

Sigmond, M., Polvani, L.M., Fyfe, J.C., Smith, C.J., Cole, J.N.S., England, M.R., 2023. Large contribution of ozone-depleting substances to global and Arctic warming in the late 20th century. Geophys. Res. Lett. 50, e2022GL100563.

Singh, A.K., Giannakoudakis, D.A., Arkas, M., Triantafyllidis, K.S., Nair, V., 2023. Composites of lignin-based biochar with BiOCl for photocatalytic water treatment: RSM studies for process optimization. Nanomaterials 13, 735.

Siwal, S.S., Kaur, H., Chauhan, G., Thakur, V.K., 2023. MXene-based nanomaterials for biomedical applications: healthier substitute materials for the future. Adv. NanoBiomed Res. 3, 2200123.

Siwal, S.S., Kaur, H., Saini, A.K., Thakur, V.K., 2022a. Recent progress in carbon dots-based materials for electrochemical energy storage toward environmental sustainability. Adv. Energy Sustain. Res. 3, 2200062.

Siwal, S.S., Mishra, K., Saini, A.K., Alsanie, W.F., Kovalcik, A., Thakur, V.K., 2022b. Additive manufacturing of bio-based hydrogel composites: recent advances. J. Polym. Environ. 30, 4501–4516.

Siwal, S.S., Sheoran, K., Mishra, K., Kaur, H., Saini, A.K., Saini, V., Vo, D.V N., Nezhad, H.Y., Thakur, V.K., 2022c. Novel synthesis methods and applications of MXene-based nanomaterials (MBNs) for hazardous pollutants degradation: future perspectives. Chemosphere 293, 133542.

Siwal, S.S., Zhang, Q.B., Devi, N., Saini, A.K., Saini, V., Pareek, B., Gaidukovs, S., Thakur, V.K., 2021a. Recovery processes of sustainable energy using different biomass and wastes. Renew. Sustain. Energy Rev. 150, 111483.

Siwal, S.S., Zhang, Q.B., Saini, A.K., Gupta, V.K., Roberts, D., Saini, V., Coulon, F., Pareek, B., Thakur, V.K., 2021b. Recent advances in bio-electrochemical system analysis in biorefineries. J. Environ. Chem. Eng. 9, 105982.

Song, W.C., Liu, M.C., Hu, R., Tan, X.L., Li, J.X., 2014. Water-soluble polyacrylamide coated-Fe_3O_4 magnetic composites for high-efficient enrichment of U(VI) from radioactive wastewater. Chem. Eng. J. 246, 268–276.

Sovacool, B.K., Schmid, P., Stirling, A., Walter, G., MacKerron, G., 2020. Differences in carbon emissions reduction between countries pursuing renewable electricity versus nuclear power. Nat. Energy 5, 928–935.

Stricher, M., Sarde, C.O., Guénin, E., Egles, C., Delbecq, F., 2021. Cellulosic/polyvinyl alcohol composite hydrogel: synthesis, characterization and applications in tissue engineering. Polymers (Basel) 13, 3598.

Sun, X.Q., Peng, B., Ji, Y., Chen, J., Li, D.Q., 2009. Chitosan(chitin)/cellulose composite biosorbents prepared using ionic liquid for heavy metal ions adsorption. AlChE. J. 55, 2062–2069.

Suopajärvi, T., Koivuranta, E., Liimatainen, H., Niinimäki, J., 2014. Flocculation of municipal wastewaters with anionic nanocelluloses: influence of nanocellulose characteristics on floc morphology and strength. J. Environ. Chem. Eng. 2, 2005–2012.

Suopajärvi, T., Liimatainen, H., Hormi, O., Niinimäki, J., 2013. Coagulation-flocculation treatment of municipal wastewater based on anionized nanocelluloses. Chem. Eng. J. 231, 59–67.

Symington, M.C., Banks, W.M., West, O.D., Pethrick, R.A., 2009. Tensile testing of cellulose based natural fibers for structural composite applications. J. Compos. Mater. 43, 1083–1108.

Tan, H.F., Ooi, B.S., Leo, C.P., 2020. Future perspectives of nanocellulose-based membrane for water treatment. J. Water Process. Eng. 37, 101502.

Tang, H., Chang, C.Y., Zhang, L.N., 2011. Efficient adsorption of Hg^{2+} ions on chitin/cellulose composite membranes prepared via environmentally friendly pathway. Chem. Eng. J. 173, 689–697.

Tang, Y.C., Ma, Q.L., Luo, Y.F., Zhai, L., Che, Y.J., Meng, F.J., 2013. Improved synthesis of a branched poly(ethylene imine)-modified cellulose-based adsorbent for removal and recovery of Cu(II) from aqueous solution. J. Appl. Polym. Sci. 129, 1799–1805.

Thakur, V.K., Thakur, M.K., Raghavan, P., Kessler, M.R., 2014. Progress in green polymer composites from lignin for multifunctional applications: a review. ACS Sustainable Chem. Eng. 2, 1072–1092.

Thakur, V.K., Voicu, S.I., 2016. Recent advances in cellulose and chitosan based membranes for water purification: a concise review. Carbohydr. Polym. 146, 148–165.

Thirumavalavan, M., Lai, Y.L., Lin, L.C., Lee, J.F., 2010. Cellulose-based native and surface modified fruit peels for the adsorption of heavy metal ions from aqueous solution: langmuir adsorption isotherms. J. Chem. Eng. Data 55, 1186–1192.

Tiwary, A., Williams, I.D., Pant, D.C., Kishore, V.V.N., 2015. Emerging perspectives on environmental burden minimisation initiatives from anaerobic digestion technologies for community scale biomass valorisation. Renew. Sustain. Energy Rev. 42, 883–901.

Tsang, Y.F., Kumar, V., Samadar, P., Yang, Y., Lee, J., Ok, Y.S., Song, H., Kim, K.H., Kwon, E.E., Jeon, Y.J., 2019. Production of bioplastic through food waste valorization. Environ. Int. 127, 625–644.

Tu, H., Yu, Y., Chen, J.J., Shi, X.W., Zhou, J.L., Deng, H.B., Du, Y.M., 2017. Highly cost-effective and high-strength hydrogels as dye adsorbents from natural polymers: chitosan and cellulose. Polym. Chem. 8, 2913–2921.

Tu, H., Zhu, M.X., Duan, B., Zhang, L.N., 2021. Recent progress in high-strength and robust regenerated cellulose materials. Adv. Mater. 33, e2000682.

Ul-Islam, M., Wajid Ullah, M., Khan, S., Kamal, T., Ul-Islam, S., Shah, N., Park, J.K., 2016. Recent advancement in cellulose based nanocomposite for addressing environmental challenges. Recent Pat. Nanotechnol. 10, 169–180.

Ullah, F., Othman, M.B.H., Javed, F., Ahmad, Z., Akil, H.M., 2015. Classification, processing and application of hydrogels: a review. Mater. Sci. Eng. C Mater. Biol. Appl. 57, 414–433.

Varghese, A.G., Paul, S.A., Latha, M.S., 2019. Remediation of heavy metals and dyes from wastewater using cellulose-based adsorbents. Environ. Chem. Lett. 17, 867–877.

Veil, J.A., Puder, M.G., Elcock, D., Redweik, R.J., 2004. A white paper describing produced water from production of crude oil, natural gas, and coal bed methane. Available at: https://publications.anl.gov/anlpubs/2004/02/49109.pdf.

Vigier, J.F., Laplace, A., Renard, C., Miguirditchian, M., Abraham, F., 2016. Uranium (III) precipitation in molten chloride by wet argon sparging. J. Nucl. Mater. 474, 19–27.

Vijayalakshmi, K., Gomathi, T., Latha, S., Hajeeth, T., Sudha, P.N., 2016. Removal of copper(II) from aqueous solution using nanochitosan/sodium alginate/microcrystalline cellulose beads. Int. J. Biol. Macromol. 82, 440–452.

Voisin, H., Bergström, L., Liu, P., Mathew, A.P., 2017. Nanocellulose-based materials for water purification. Nanomaterials 7, 57.

Wang, B., Wen, J.L., Sun, S.L., Wang, H.M., Wang, S.F., Liu, Q.Y., Charlton, A., Sun, R.C., 2017a. Chemosynthesis and structural characterization of a novel lignin-based bio-sorbent and its strong adsorption for Pb (II). Ind. Crops Prod. 108, 72–80.

Wang, D., 2019. A critical review of cellulose-based nanomaterials for water purification in industrial processes. Cellulose 26, 687–701.

Wang, L., Song, H., Yuan, L.Y., Li, Z.J., Zhang, Y.J., Gibson, J.K., Zheng, L.R., Chai, Z.F., Shi, W.Q., 2018. Efficient U(VI) reduction and sequestration by Ti_2CT_x MXene. Environ. Sci. Technol. 52, 10748–10756.

Wang, L.L., Chen, D., Jiang, K., Shen, G.Z., 2017b. New insights and perspectives into biological materials for flexible electronics. Chem. Soc. Rev. 46, 6764–6815.

Wang, L.Y., Wang, M.J., 2016. Removal of Heavy Metal Ions by Poly(vinyl alcohol) and Carboxymethyl Cellulose Composite Hydrogels Prepared by a Freeze-Thaw Method. ACS Sustainable Chem. Eng. 4, 2830–2837.

Wang, Q.Q., Zhu, J.Y., Reiner, R.S., Verrill, S.P., Baxa, U., McNeil, S.E., 2012. Approaching zero cellulose loss in cellulose nanocrystal (CNC) production: recovery and characterization of cellulosic solid residues (CSR) and CNC. Cellulose 19, 2033–2047.

Wang, S., Ran, Y.H., Lu, B.H., Li, J., Kuang, H.R., Gong, L., Hao, Y.H., 2020a. A review of uranium-induced reproductive toxicity. Biol. Trace Elem. Res. 196, 204–213.

Wang, Y., Xiong, Y., Wang, J.Y., Zhang, X.D., 2017c. Ultrasonic-assisted fabrication of montmorillonite-lignin hybrid hydrogel: highly efficient swelling behaviors and super-sorbent for dye removal from wastewater. Colloids Surf. A 520, 903–913.

Wang, Y., Zhang, Y.P., Li, Q., Li, Y.X., Cao, L.X., Li, W.L., 2020b. Amidoximated cellulose fiber membrane for uranium extraction from simulated seawater. Carbohydr. Polym. 245, 116627.

Wang, Y.G., Yadav, S., Heinlein, T., Konjik, V., Breitzke, H., Buntkowsky, G., Schneider, J.J., Zhang, K., 2014. Ultra-light nanocomposite aerogels of bacterial cellulose and reduced graphene oxide for specific absorption and separation of organic liquids. RSC Adv 4, 21553–21558.

Williams, G.I., Wool, R.P., 2000. Composites from natural fibers and soy oil resins. Appl. Compos. Mater. 7, 421–432.

Won, J.S., Prasad, C., Jeong, S.G., Rosaiah, P., Reddy, A.S., Ahmad, Z., Sangaraju, S., Choi, H.Y., 2023. Recent advances in the development of MXenes/cellulose based composites: a review. Int. J. Biol. Macromol. 240, 124477.

Wu, F.C., Tseng, R.L., Juang, R.S., 2010. A review and experimental verification of using chitosan and its derivatives as adsorbents for selected heavy metals. J. Environ. Manage. 91, 798–806.

Wu, M.B., Liu, S.C., Fei, J.Y., Ye, H., Ma, L.L., 2022a. Natural cellulose-based microspheres decorated with amidoxime groups for decontamination of radioactive wastewater. Appl. Surf. Sci. 597, 153659.

Wu, S.P., Shi, W.J., Li, K.H., Cai, J.W., Chen, L.Y., 2022b. Recent advances on sustainable bio-based materials for water treatment: fabrication, modification and application. J. Environ. Chem. Eng. 10, 108921.

Xiong, R., Wang, Y.R., Zhang, X.X., Lu, C.H., 2014. Facile synthesis of magnetic nanocomposites of cellulose@ultrasmall iron oxide nanoparticles for water treatment. RSC Adv 4, 22632–22641.

Yan, M.F., Huang, W.X., Li, Z.L., 2019. Chitosan cross-linked graphene oxide/lignosulfonate composite aerogel for enhanced adsorption of methylene blue in water. Int. J. Biol. Macromol. 136, 927–935.

Yang, L.S., Xiao, H.Y., Qian, Y.C., Zhao, X.L., Kong, X.Y., Liu, P., Xin, W.W., Fu, L., Jiang, L., Wen, L.P., 2022. Bioinspired hierarchical porous membrane for efficient uranium extraction from seawater. Nat. Sustain. 5, 71–80.

Yang, S.P., Fu, S.Y., Liu, H., Zhou, Y.M., Li, X.Y., 2011. Hydrogel beads based on carboxymethyl cellulose for removal heavy metal ions. J. Appl. Polym. Sci. 119, 1204–1210.

Zare, E.N., Mudhoo, A., Ali Khan, M., Otero, M., Ali Bundhoo, Z.M., Navarathna, C., Patel, M., Srivastava, A., Pittman Jr, C.U., Mlsna, T., Mohan, D., Makvandi, P., Sillanpää, M., 2021. Water decontamination using bio-based, chemically functionalized, doped, and ionic liquid-enhanced adsorbents: review. Environ. Chem. Lett. 19, 3075–3114.

Zhang, G.L., Yi, L.J., Deng, H., Sun, P., 2014a. Dyes adsorption using a synthetic carboxymethyl cellulose-acrylic acid adsorbent. J. Environ. Sci. (China) 26, 1203–1211.

Zhang, K., Li, Z.J., Kang, W.M., Deng, N.P., Yan, J., Ju, J.G., Liu, Y., Cheng, B.W., 2018. Preparation and characterization of tree-like cellulose nanofiber membranes via the electrospinning method. Carbohydr. Polym. 183, 62–69.

Zhang, L.L., Lu, H.L., Yu, J.A., McSporran, E., Khan, A., Fan, Y.M., Yang, Y.Q., Wang, Z.G., Ni, Y.H., 2019a. Preparation of high-strength sustainable lignocellulose gels and their applications for antiultraviolet weathering and dye removal. ACS Sustainable Chem. Eng. 7, 2998–3009.

Zhang, M., Ding, C.C., Chen, L.H., Huang, L.L., 2015. Preparation of tannin-immobilized collagen/cellulose bead for Pb(II) adsorption in aqueous solutions. Bioresources 10.

Zhang, X.Y., Gu, P., Liu, Y., 2019b. Decontamination of radioactive wastewater: state of the art and challenges forward. Chemosphere 215, 543–553.

Zhang, X.Y., Liu, Y., 2020. Nanomaterials for radioactive wastewater decontamination. Environ. Sci.: Nano 7, 1008–1040.

Zhang, Y.X., Nypelö, T., Salas, C., Arboleda, J., Hoeger, I.C., Rojas, O.J., 2013. Cellulose nanofibrils. J. Renew. Mater. 1, 195–211.

Zhang, Z., Sèbe, G., Rentsch, D., Zimmermann, T., Tingaut, P., 2014b. Ultralightweight and flexible silylated nanocellulose sponges for the selective removal of oil from water. Chem. Mater. 26, 2659–2668.

Zhao, S.L., Yuan, Y.H., Yu, Q.H., Niu, B.Y., Liao, J.H., Guo, Z.H., Wang, N., 2019. A dual-surface amidoximated halloysite nanotube for high-efficiency economical uranium extraction from seawater. Angew. Chem. Int. Ed. 58, 14979–14985.

Zhou, D., Zhang, L.N., Zhou, J.P., Guo, S.L., 2004. Cellulose/chitin beads for adsorption of heavy metals in aqueous solution. Water Res 38, 2643–2650.

Zhou, K., Zhang, Q.G., Li, H.M., Guo, N.N., Zhu, A.M., Liu, Q.L., 2014. Ultrathin cellulose nanosheet membranes for superfast separation of oil-in-water nanoemulsions. Nanoscale 6, 10363–10369.

Zhou, Y.M., Jin, Q., Hu, X.Y., Zhang, Q.Y., Ma, T.S., 2012a. Heavy metal ions and organic dyes removal from water by cellulose modified with maleic anhydride. J. Mater. Sci. 47, 5019–5029.

Zhou, Y.M., Zhang, L.L., Fu, S.Y., Zheng, L.M., Zhan, H.Y., 2012b. Adsorption behavior of Cd^{2+}, Pb^{2+}, and Ni^{2+} from aqueous solutions on cellulose-based hydrogels. Bioresources 7, 2752–2765.

Zhu, C.P., Wang, W., Wu, Z.J., Zhang, X.C., Chu, Z.Z., Yang, Z.H., 2023. Preparation of cellulose-based porous adsorption materials derived from corn straw for wastewater purification. Int. J. Biol. Macromol. 233, 123595.

Zhu, H.C., Zhang, Y., Yang, X.G., Liu, H.Y., Zhang, X.M., Yao, J.M., 2015. An eco-friendly one-step synthesis of dicarboxyl cellulose for potential application in flocculation. Ind. Eng. Chem. Res. 54, 2825–2829.