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Review Paper

Bio-Based Filter Materials for Wastewater Treatment - A Review

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Abstract

Clean water is essential to life and a crucial requirement for a sustainable society. Water bodies are often contaminated with a diverse range of pollutants resulting from both natural and anthropogenic activities. Different methods of water remediation have been proposed, including adsorption. Among the materials developed for contaminant adsorption from wastewater, bio-based filter materials offer innovative and sustainable solutions for wastewater treatment. These materials combine biological and engineered components to enhance pollutant removal, reduce operational costs, and promote environmental sustainability. This review explores bio-based filter materials, their components, properties, comparative efficiencies, challenges, and future research directions. In the review, some chitosan-based bio-filters were found to efficiently remove over 90% of copper and lead ions from waste effluents. Also, cellulose and lignin-based bio-filters were reported to efficiently remove over 80% of organic and inorganic contaminants from waste effluents without secondary pollution. Comparably, bio-based filter materials have high stability and adaptability to varying environmental conditions. However, this development faces challenges and setbacks, such as limitations to large-scale deployment. Insufficient mechanistic understanding of material-pollutant interactions and a lack of comprehensive environmental impact assessment through life cycle analysis on these vast bio-based materials limit the field application and large-scale real-life on-site deployment.

Keywords: Bio-based filters, Adsorption, Water treatment, Wastewater, Contaminants

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1. Introduction

Recent environmental challenges have raised concerns about the sustainability and habitability of our planet, thus prompting research into more eco-friendly solutions for global development. Amongst the many sources of environmental pollution are the rapid increase in population, accelerated urbanization, and burgeoning industrialization. These factors have led to high demand for quality water. Approximately 71% of the Earth's surface is covered with water; however, access to quality and clean water continues to pose a challenge to the global population, particularly in developing countries (UNICEF, 2021). Research has also shown that exposure to contaminated water has contributed to a 2.5% mortality rate globally (Andrew and Dhakal, 2022; Loh et al., 2021). Technological advancements have led to innovations that can remediate water stress, including the reclamation of wastewater. Wastewater is water obtained from the end product of industrial processes, often laced with toxic contaminants like heavy metals, organics, and biological pollutants (Onchieku, 2023; Tsiropoulos et al., 2015). This water, when discharged into water bodies, destroys biota and poses health risk to humans through direct ingestion, skin contact, and ingestion through the secondary food chain. Advances in technology have led to the removal of these pollutants from the water either for reuse or before discharge to the environment. Traditional treatment methods like coagulation, flotation, sedimentation, and chlorination, though effective, often involve high energy consumption and chemical usage, which contribute to environmental degradation (Gude, 2016), leading to the use of modern techniques such as adsorption, membrane filtration, and chemical precipitation. According to Kumar et al. (2022), filtration offers one of the most efficient methods of water and wastewater treatment. However, over the years, fabricating effective and efficient materials for water filtration without a ripple effect on the environment continues to pose challenges to scientists due to the non-degradability of synthetic materials, leading to the introduction of biobased filter materials (Hammes et al., 2019). These materials are derived from biological components to enhance pollutant removal, reduce operational costs, and promote environmental sustainability due to their biodegradable nature, low cost, and ability to adsorb or degrade contaminants (Thompson et al., 2019). Bio-based filters are highly versatile, with many functional groups that allow modification (Zhang et al., 2017) and since they are derived from renewable agricultural sources, they encourage afforestation and contribute to cleaner air and water, offering the potential to outperform their synthetic counterparts. However, their performance can be influenced by factors such as pH, temperature, and pollutant concentration (Zhao et al., 2019; Gough et al., 2021; Wu et al., 2022). This review explores the origin and characteristics of bio-based filter materials, highlighting their efficiency in the removal of various contaminants from water, selective advantages and limitations compared to conventional filtration materials, their role in sustainable development, and innovations for improving their efficiency in water purification.

Water Treatment Technologies

The conventional water treatment technologies involve primary treatment of wastewater, which includes rough filtration through screens and sieves, followed by removal of suspended solids through sedimentation. Coagulants can be added to enhance sedimentation. Secondary treatment is then performed to degrade the organic matter and nutrients of wastewater into stable forms through biological activity (bacteria). Trickling filters, activated sludge, membrane bioreactors, and rotating biological contactors are the common approaches. Tertiary treatment includes disinfection employing chlorine, UV radiation, ozonation, filters, etc. Waste stabilization ponds, constructed wetlands, and oxidation ditches are non-conventional methods for wastewater treatment (Fahad et al., 2019). Although these traditional water treatment methods have specific advantages, they also have certain disadvantages. Coagulation and flocculation effectively reduce turbidity and remove suspended particles, but they may produce a significant amount of toxic sludge, which requires proper disposal. Sedimentation can reduce water treatment costs and the need for additional chemicals but cannot effectively remove smaller particles and microbes. Filtration methods, such as sand filtration, may not completely eliminate pathogens and require frequent cleaning and maintenance of filters. Additionally, chlorination is widely used to kill germs, but it is a potent biocide and unsafe. Modern techniques like Advanced oxidation techniques offer fast reaction rates and reduced toxicity of organic pollutants, but they are expensive and require careful dose calculations due to their complex chemistry. Ion exchange is an eco-friendly method of neutralizing acidic or basic water, but it faces fouling, bacterial and chlorine contamination, and inadequate regeneration. Anaerobic treatment offers a low-environment-friendly approach but cannot remove inorganic components and generate volatile acids. Microbial treatment is another environment-friendly method used to remove pollutants from water, but it has a short lifespan, is costly, and can result in fouling and low production rates. In contrast, adsorption and membrane filtration stand out for their effectiveness and versatility. Adsorption offers high removal efficiency, selectivity, and the potential for regeneration, while membrane filtration provides a reliable method for removing suspended solids, pathogens, and dissolved substances. Therefore, adsorption and membrane filtration technologies have played a crucial role in developing modern water treatment processes, ensuring the delivery of clean and safe drinking water to communities worldwide. These two technologies, however, have been limited by the fabrication of cost-effective and eco-friendly media - adsorbent and membrane - for the filtration process. Also, the end-of-life cycle of the filtration media is not clearly defined.

Bio-based filter Materials

Bio-based filter materials refer to filter materials derived from natural sources like cellulose, chitin, silk, soy, and keratin, with specific applications in filtration as alternatives to synthetic materials (Gough et al., 2021) These materials, sourced from proteins and polysaccharides belong to a higher class of materials called 'bio-based materials". Bio-based materials provide an extensive range of possible products such as structural wood or timber, paints, varnishes, adhesives, insulation, and finishing products, which range from bioplastics, biopolymers, biofibers, and bio composites. In this review, bio-based filter materials (BFM) only refer to micro- and nanomaterials derived from cellulose, chitosan, and keratin used as water and wastewater filtration membranes.

History of Biobased Filter Materials

The history of biobased filter materials in water filtration dates back to ancient civilizations. The Ancient Egyptians, 2000BC to 400BC, used sand, gravel, charcoal, and plant fibers as filter media, and later on, the use of linen clothes as filters was introduced. A summary of the trends in the progress of biobased materials as filters in water treatment is given in **Table 1**. Below Modern technology has built on ancient civilizations to fabricate and modify filter materials to suit the target contaminant and application.

Table 1. Development in the use of filter materials in water filtration

Era	Material/Innovation	Key Contributions	Ref.
2000 BC – 400 BC (Ancient Civilisations)	Charcoal, sand, cloth filtration	Ancient Egyptians used sand and charcoal for water clarity; Hippocrates' "Hippocratic sleeve" for cloth filtration	Ndabigengesere, & Narasiah (1998)
500 AD – 1500 AD (Medieval Period)	Woven cloth, plant fibers	Household sieving continued; Arabic scholars documented boiling and filtration	Ndabigengesere, & Narasiah (1998)
1804 – 1829	Slow sand filtration	First municipal slow sand filter (Paisley, Scotland, John Gibb); bacterial removal	Budnyak et al., 2020
Late 19th Century	Ceramic and charcoal household filters	Ceramic pots lined with charcoal for domestic purification	Siregar, 2018
1979 – 1984	Moringa seed coagulant	Sudan field trials showed Moringa oleifera seeds remove turbidity and bacteria	Wu et al., 2023
1980s	Expanded Moringa trials	Madsen, Schlundt & Omer confirmed improved water quality in rural/emergency settings	Madsen et.al., 1987
1990s	Other plant-based coagulants	Nirmali seeds, cactus mucilage tested in Asia, Africa, Latin America	Wu et al., 2023
2000 – 2005	Coconut husk fiber filters	Coconut coir for turbidity, color, and heavy metal removal	Olowoyo et al., 2012
2005-2010	Rice husk ash and jute fiber filtration	Tested for arsenic, iron, and turbidity removal in Asia	Mansurov, et al. 2022
~2010	Nanocellulose membranes	Cellulose-based ultrafiltration removed metal ions, viruses, and organics	Voisin, et al., 2017
2015	Biochar–sand composite filters	Enhanced adsorption of dyes, pesticides, and pathogens	Gough et al., 2021; Li et al., 2017
2017	Biochar-based advanced composites	Biochar with polymer/ceramic matrices targeted PFAS, pharmaceuticals, and emerging contaminants	Kim et al., 2023

Components of Biobased Filter Materials

Bio-based filter materials are composed of certain biopolymeric materials and complex polysaccharides such as cellulose, chitin, silk, soy, lignin, hemicellulose, and keratin (Gough et al., 2021). These biological macromolecules form the basic framework for the biofilter materials due to their versatility, stability, and tunable surface chemistry and functionality. Biobased filter materials are abundant in nature and contain important functional groups like hydroxyl, carboxyl, and amino groups. These functional groups are important for modifying and absorbing contaminants in water (Al-Gethami et al., 2024). These properties can be described based on the components derived using each of the primary sources.

a. Cellulose—This is one of the most abundant biopolymers, made up of plant and animal fibers, primarily from wood, annual plants, microbes, and animals. Cellulose is a long-chain polysaccharide consisting of β-D-glucopyranose units linked together by β-1,4 glycosidic linkages (**Figure 1**). It is composed of two hydroxyl groups with a planar structure, making it semicrystalline (Lu et al., 2018).

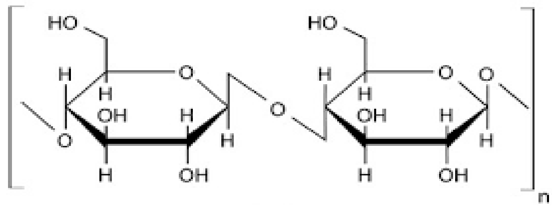

Figure 1. Structure of Cellulose (Ateia et al., 2018)

Cellulose is insoluble in water due to the strong hydrogen bond between the cellulose chains and van daar waals forces in the glucose units. The dynamic structure of the primary cell wall of plant fibers combines to form the complex structure of cellulose, which gives it distinct physical properties like high mechanical strength (Heinze, 2015). The inter- and intramolecular bonds within the cellulose macromolecules confer it with structural rigidity and crystallinity. Cellulose can be modified by chemical treatment to improve efficiency (Salama et al., 2015). Due to its availability from agricultural sources, which can be renewed by growing plants and trees, cellulose, amongst other biobased materials, can easily be employed as cheap adsorbents in the removal of target contaminants like heavy metals and dyes.

b. Chitosan- chitosan is derived from chitin, the most widely occurring biopolymer in nature after cellulose. It can be found in a range of eukaryotic species such as crustacea, insects, and fungi. **Figure 2** is the structure of chitosan. The reactive groups found in chitosan are primary amino groups (C2) and primary and secondary hydroxyl groups (C6, C3). Glycosidic bonds and the acetamide group can also be considered functional groups. These functional groups allow for a great number of modifications, producing polymers with new properties and behaviors (Wu et al., 2019).

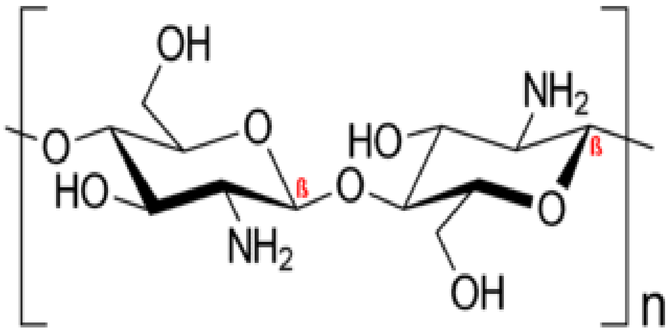

Figure 2. Structure of Chitosan (Wu et al. 2019)

Chitosan is the only polycation in nature, and its charge density depends on the degree of acetylation and pH of the media. The solubility of the polymer depends on the acetylation degree and molecular weight (Lizardi-

Mendoza et al., 2016). Chitosan oligomers are soluble over a wide pH range, from acidic to basic ones (i.e., physiological pH 7.4). The presence of large amounts of protonated $-NH_2$ groups on the chitosan structure accounts for its solubility in acid aqueous media. Its viscosity depends on the molecular weight of the polymer and deacetylation degree and decreases as the molecular weight of chitosan is reduced, making it easily modified for a wide range of applications, including the removal of toxic contaminants from water (Bakshi et al., 2020; Kumari & Kishor, 2020; Saheed et al., 2021; Wang et al., 2020).

c. Keratin- Keratins refer to a group of insoluble and filament-forming proteins produced in certain epithelial cells of vertebrates; they belong to the superfamily of intermediate filament proteins and form the bulk of the horny layer of the epidermis and the epidermal appendages such as hair, nails, horns, and feathers. Based on X-ray diffraction, keratins can be classified into a-pattern, b-pattern, feather-pattern and amorphous pattern (Ali et al., 2022). The general structure of Keratin is presented in **Figure 3**.

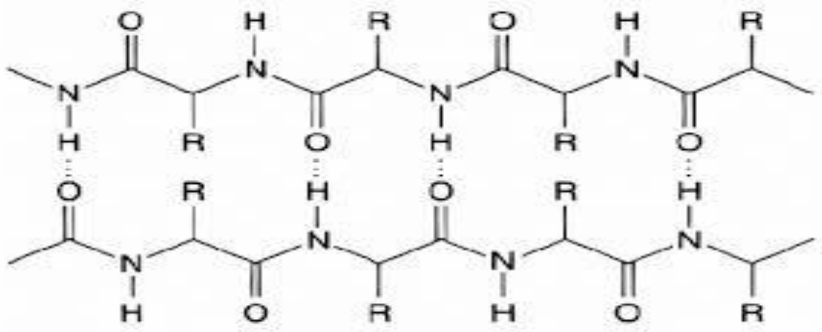

Figure 3. Structure of Keratin (Ali et al., 2022)

Keratin exhibits exceptional mechanical functions depending on the host animals originating from the complex hierarchical structures, including the filament-matrix structure at the nanoscale and the diverse organizations of keratinized cells at micro and macroscales (Hill et al., 2010). It is one of the most important structural proteins in nature and can be classified into α-helices and β-pleated sheets. The protofilaments polymerize to form the basic structural unit, the intermediate filament (IF), and the alignment of the IFs influences the mechanical properties of increased tensile strength, which makes it a suitable material for contaminant filtration (McKittrick et al., 2012).

Types of Bio-Based Filter Materials

Bio-based filter materials can be categorized based on their source and processing methods:

Natural Plant-Based Materials: These are plant materials that can be used to filter water. They are a biodegradable, sustainable, cost-efficient alternative for wastewater treatment. They include Coconut coir, sawdust, and rice husks and are widely used due to their high availability and porosity (Bhatnagar et al., 2015). These materials are effective in removing suspended solids and heavy metals (Gupta & Ali, 2012). Israel and Okon (2014) have reported on the use of coconut coir dust for the removal of trace metals from simulated and paint waste effluent. Also, coir dust from coconut and activated carbon from plantain peels have been reported to efficiently remove zinc, lead, and organic dyes from contaminated water (Inam et al., 2015; Isreal & Okon, 2014; Etim et al., 2013).

Biopolymers: Biopolymers are defined as polymers formed under natural conditions during the growth cycles of all organisms. Therefore, they are also named natural polymers. They are formed within cells by complex metabolic processes. For materials applications, cellulose and starch are most interesting. However, there is increasing attention in more complex hydrocarbon polymers produced by bacteria and fungi, such as xanthan, curdlan, pullulan, chitin, chitosan and hyaluronic acid (Gopal Rao et al., 2014). They also include Chitosan, alginate, and cellulose are examples of biopolymers with excellent adsorption properties (Rinaudo, 2006). Their surface functional groups can bind to a variety of pollutants, including dyes and heavy metals (Ngah & Fatinathan, 2010). The main properties of biopolymers to be used as filter membranes or adsorbents for environmental applications are related to their high permeability for capturing airborne or water contaminants

(Lippi et al., 2022). Also, their outstanding mechanical and thermal stability, better resistance to diverse pH conditions (Xiao et al., 2014), biodegradability, swelling capacity, tunability, high functionality and low cost (Biswas & Priyanka, 2022).

Biochar: Biochar are carbon-rich materials obtained from pyrolysis of biomass. Biochar has a high surface area and pore volume, making it an excellent adsorbent for organic pollutants (Lehmann & Joseph, 2015). Biochar is also known for its ability to support microbial activity, enhancing biodegradation (Schmidt et al., 2014). Okon et al. (2025) reported on the use of biochar-bentonite composite as hybrid biofilter for wastewater treatment. Nautiyal et al. (2016) used Spirulina platensis algae residue from the biodiesel industry to prepare biochar and examined its adsorption capacity for Congo red. The results showed that algae-based biochar had comparable removal efficiency to commercial activated carbon and was an effective method for the production of biochar adsorbents in a sustainable manner from the algae biodiesel industry.

Composite Materials: Composite materials are materials made from two or more different materials that are combined to create a new material with different properties. Polymer-based composites like chitosan-clay mixtures, activated carbon fibers, zeolites, metal-organic frameworks, and various nanocomposites incorporating materials like graphene or clay particles which are effective in adsorbing and removing pollutants like heavy metals, organic contaminants, and nutrients from wastewater. Combining bio-based materials with nanoparticles or other adsorbents can improve their mechanical strength and adsorption capacity (Lu et al., 2018). Okon et al, 2025 conducted a study on the column treatment of BPA effluent both real and simulated using cyclodextrine-based biofilter modified with doped titanium magnetic montmorillonite nanocomposite as a biobased sustainable and ecofriendly filter material. Wu et al. (2019) synthesized nanochitin-contained magnetic chitosan (FPCC) microfibers by injection gelation process and used it to remove Ni (II) ion from aqueous solution. The FPCC magnetic microfibers removed 99.7% Ni (II) ions within 10 h at 293 K (adsorbent dosage: 1 g, pH: 4.1). The separation factor (RL) value indicates the tendency of the adsorption process. The calculated value of RL for the FPCC adsorbent indicates its favorable adsorption to Ni (II) ions.

Synthesis and Characterization of Biobased Filter Materials

The choice method of synthesis of biobased filter material depends on the desired results, whether micro or nano material, the cost implication, time efficiency, and sustainability. Generally, the process starts with the collection and preparation of apart from the animal and plant sources, extraction of the needed part, and thereafter, mechanical and or chemical modifications such as electrospinning, phase inversion are applied to have the required specification, such as porosity, and particle size. Characterization gives information about the chemical properties of the materials. Characterization techniques include Fourier Transform Infrared Electroscopy (FTIR), Scanning Electron Microscopy (SEM), AND Brunet Emmet Teller (BET) for surface analysis, and functional groups.

Efficiency of BFM in water treatment

Application of BFM in water treatment

Biobased filters have demonstrated proficiency in targeting a range of contaminants, encompassing VOCs, microplastics, heavy metals, and organic pollutants, contributing significantly to environmental remediation efforts Wu et al. (2019). In **Table 2**, Al-Gethami et al., 2024 reported **t**he use of Thiol-functional nanocrystals derived from chitosan as biobased filters in the removal of Cu and Pb ions from environmental wastewater. The removal efficiency was 90.58% and 90.21% respectively for Cu and Pb showed that the synthesized biobased nanocrystal was an efficient filter material for wastewater treatment and the adsorption efficiencies did not reduce after four consecutive cycles of adsorption and desorption (Al-Gethami et al., 2024). The authors also reported that the synthesized material was limited in efficiency of removal of metal ions at pH above 7 leading to precipitation. Also, from cellulose, Ateia et al., (2018) synthesized a poly(ethylenimine)- functionalized microcrystal as a biobased filter material for removal of per- and poly- fluoroalkyl substances from industrials wastewater. The material showed great promise for versatile adsorption material with adsorption efficiency ranging from 80-85% and was found to be stable under different adsorption conditions. However, one drawback was the slow removal at low adsorbate initial concentrations with PFOA removal efficiency of only 11 ± 10% after 1 h and an equilibrium time of 15–24 h. Hong et al (2021) has reported on synthesis of cylindrical 3D cellulose nanofibril (PEI@CNF) aerogel for continuous copper ions adsorption from wastewater. The reported adsorption capacity was 13.4 mg/g and was said to proceed through the pseudo-second order reaction model leading to predominantly chemisorption process. However, this low adsorption was said to be as a result lack of specific surface area and the adsorption rate decreased when the PEI content was increased beyond 1 because of the decrease in specific surface area. Also, according Hong et al. (2021), The continuous removal of Cu^{2+} in the column operation mode was demonstrated for the practical use of the PEI@CNF aerogel in real life applications. Acryl type column was packed with the cylindrical aerogel PEI@CNF which allowed for larger contact area of the wastewater on the adsorbent compared to beaded or pellets which allow empty space for effluents to pass without contact with adsorbent. In the column experiment, the breakthrough curve showed high breakthrough and exhaustion time and could treat up to 30-88 bed volume (BV) before reaching exhaustion. The column was found to be reusesable and retains its optimum efficiency after five cycles of adsorption-desorption thus making the CNF aerogel practically feasible for real industrial application. Other biobased materials show great promise in the removal of organic dyes with high removal capacity (Li et al., 2017; Marrakchi et al., 2016; Salama et al., 2015). Budnyak et al. (2020), reported on the synthesis of membrane-filter composite from kraft lignin and silica for removal of cobolt (II) ions from wastewater by bath adsorption. From their results, the Co(II) adsorption onto pure silica and kraft lignin showed that the capacity of the composite is three times larger than the sum of the capacities of initial components alone: at 22 °C, the capacities of pure silica and kraft lignin were 3.37 and 2.52 mg/g, respectively, whereas for the composite it is 17.9 mg/g. Bio-based filter materials have also been found to be sustainable through a comprehensive life cycle assessment (LCA). Zakrisson et al. (2024) reported on life cycle assessment of biochar filters for on-site wastewater treatment. They employed parameterised life cycle assessment (LCA) approach and compared the results to that of sand bed filters. The eutrophication impact of the biochar filters was similar to that of the sand filter, while the acidification impact was generally slightly higher than that of the sand filter in sensitive areas, and lower in normal areas. The climate impact of the biochar filter varied considerably, from substantially higher to lower than that of the sand filter, depending on specific scenario. A few scenarios in which biochar filters had lower overall impacts than the sand filter were identified.

Table 2. Efficiency of different biobased filter materials in removing various contaminants

Biofilter	Source	Contaminant	Adsorption capacity (mg/g)	Efficiency (%)	Reference
Thiol-functionalized nanocrystals	Chitosan	Cu(II) ions	-	90.58	Al-Gethami et al., 2024
Thiol-functionalized nanocrystals	Chitosan	Pb(II) ions	-	90.21	Al-Gethami et al., 2024
Poly(ethylenimine)-functionalized cellulose microcrystals	Cellulose	Per-and poly-fluoroalkyl substances	-	70-80	Ateia et al., 2018
cellulose-derived graphene-like carbon	Cellulose	Rhodamine B	-	80	Kim et al., 2023
cellulose-derived graphene-like carbon	Cellulose	Congo Red		80	Kim et al., 2023
(CH-PAA-T) thermal cross-linking chitosan	Chitosan	Methylene blue (MB)	990.1	-	Li et al., 2017

Table 2. continued

and polyacrylic acid (CH-PAA-T) thermal cross-linking chitosan and polyacrylic acid	Chitosan	Cu^{2+}	135.9	-	Li et al., 2017
CMC-g-PDMAEMA hydrogel	Cellulose	Methyl blue	-	90	Salama et al., 2015
Cross-linked chitosan/sepiolite composite	Chitosan	Methylene blue	-	40	Marrakchi et al., 2016
Cross-linked chitosan/sepiolite composite	Chitosan	Reactive orange 16	-	90	Marrakchi et al., 2016
Membrane-filtered Kraft Lignin-Silica hybrids	Lignin	Co	18	70-80	Budnyak et al., 2020
CS–PEO/TOC	Cellulose and Chitosan	Cu(II) ions	12	27	Cárdenas Bates et al., 2021
Biochar	cellulose				Zakrisson et al., 2024

Comparison with Synthetic Filter Materials and Natural Filter Materials

Bio-based filter materials obtained from plant and animals can be compared to natural filter materials, such as sand, clay, and synthetic filter materials such as those obtained from fossil fuels such as polypropylene and polyesters fibers with respect to their efficiency, durability, sustainability, cost efficiency and tenability for targeted applications (Zhang et al., 2019) Their respective advantages and disadvantages are highlighted in **Table 3.** The comparison is primarily based on the properties of these filter materials including the pore size and surface areas and can also be dependent on the method of contaminant removal. For instance, in adsorption, the different organic functional group offers more available binding sites. Whereas, synthetic filter materials can easily undergo surface modification to provide binding sites (Sharma et al., 2020; Park et al., 2021).

Table 3. Comparison of the properties of Natural, Synthetic and Biobased Filter Materials

Properties	Natural Filter Materials	Biobased Filter Materials	Synthetic Filter Materials	References
Efficiency	Moderate; depends on pore size and material composition	High; often enhanced with functional groups for better performance	Very high; engineered for specific filtration applications	Mousa et al., 2020; Zhang et al., 2019
Modification	Limited; can be improved by surface treatments (e.g., activation, chemical impregnation)	Moderate; can be functionalized for better adsorption and biodegradability	Highly modifiable; can be tailored at a molecular level for specific filtration needs	Ali et al., 2021; Liu et al., 2018
Fabrication	Simple; often requires minimal processing (e.g., drying, cutting)	Requires processing such as fiber extraction, blending, or coating	Complex; involves industrial processes like electrospinning, polymerization, and nanofabrication	Gopakumar et al., 2017; Das et al., 2022

Table 3. continued

Properties	Natural Filter Materials	Biobased Filter Materials	Synthetic Filter Materials	References
Characteristics	Eco-friendly, biodegradable, and cost-effective; may have inconsistent performance due to natural variability	Renewable, biodegradable, and can be engineered for specific filtration properties	Durable, high-performance, and customizable, but may pose environmental concerns due to non-biodegradability	Sharma et al., 2020; Park et al., 2021

Challenges and Future Trends in Bio-Based Filter Materials for Wastewater Treatment

Despite their advantages, bio-based filter materials face several challenges which include developing methods for large-scale production and application (Zhang et al., 2017). As reported by Zhang et al. (2019), any strategy for extensive adoption of bio-based filters for applications in environmental remediation is often constrained by the lack of large-scale field data on soil quality, crop response and environmental impact. Influences of bio-based filter materials application as a strategy for environmental management are often inconclusive or even contradictory. Example, while biobased filter materials are more environmentally safe, the cutting of trees for its production have negative environmental impact, also the end of life of the materials is yet to be understood with regards to its fate in the environmental. (Lu et al., 2018). The lack of understanding the interaction between bio-based materials and different types of pollutants may hinder performance optimization (Zhao et al., 2019). Other challenges facing bio-based filter materials are lack of comprehensive assessment of environmental impacts through life cycle analysis to ensure true sustainability (Thompson et al., 2019).

Looking to the future of this sustainable technology for wastewater treatment requires holistic approach to mitigate its challenges and enhance efficiency. Emerging trends in the development of bio-based filter materials indicate a focus on advanced composite designs, nanotechnology integration, and functional enhancements for intelligent filtration systems. In light of the aforementioned, advanced composites options are being explored by researchers as hybrid bio-based materials combined with nanomaterials, such as graphene oxide and metal-organic frameworks, for improved adsorption and mechanical strength (Wang et al., 2023). Other advances include self-regenerative filters leading to development of materials with self-regeneration capabilities to enhance long-term performance and reduce maintenance costs (Liu et al., 2022). Incorporation of sensors as smart monitoring systems into bio-based filters for real-time monitoring of pollutant levels and operational efficiency (Zhang et al., 2017). Also, with recourse to green chemistry, future focus will be on eco-friendly and energy-efficient production processes for bio-based filter materials to ensure sustainable manufacturing practices (Wang et al., 2023). Moreover, field applications and long-term studies will increase emphasis on pilot-scale and long-term studies to validate the performance of bio-based filter materials under real-world conditions (Liu et al., 2022).

Conclusion

Bio-based filter materials represent a promising solution for sustainable wastewater treatment. Their ability to remove a wide range of pollutants, combined with their environmental benefits, makes them an attractive alternative to natural and synthetic filter materials. The presence of functional groups offers a more binding site in traditional application like the adsorption of target contaminants. Also the primary sources which include plants and animals make them environmentally sustainable. However, associated impacts like deforestation also pose possible negative impact on the environment. The dart literature on end-of-life cycle with respect to the impact on the environment poses a challenge. Continued research and development are necessary to overcome existing challenges and unlock their full potential. Future advancements are likely to focus on intelligent, self-regenerative, and highly efficient bio-based filters, driving the next generation of green wastewater treatment technologies.

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Authors Contribution

Conceptualization and Design: C. I. E, E. J. I., and S.E.S. Methodology and data curation: O.E. O., and C.I.E Investigation, data collection, analysis and interpretation: C.I.E., O.E.O. Writing original draft: O.E.O., C.I.E., Writing, editing and review: O.E.O., C.I.E, S.E.S and E.J.I. Funding acquisition: E.J.I., S.E.S.

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Declaration of Competing Interests

There is no conflict of interest as regards that data and information in this manuscript.

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