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Review

Progress in the Sustainable Development of Biobased (Nano)materials for Application in Water Treatment Technologies

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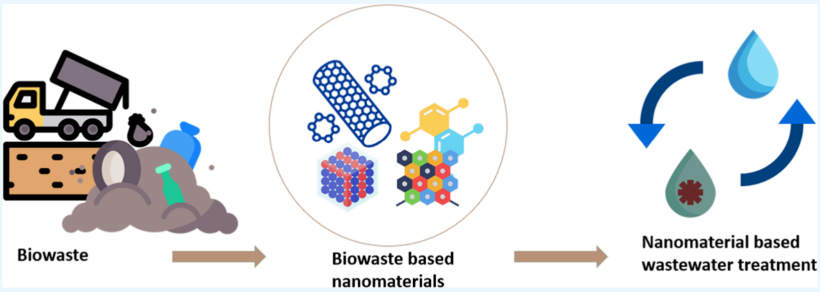

ABSTRACT: Water pollution remains a widespread problem, affecting the health and wellbeing of people around the globe. While current advancements in wastewater treatment and desalination show promise, there are still challenges that need to be overcome to make these technologies commercially viable. Nanotechnology plays a pivotal role in water purification and desalination processes today. However, the release of nanoparticles (NPs) into the environment without proper safeguards can lead to both physical and chemical toxicity. Moreover, many methods of NP synthesis are expensive and not environmentally sustainable. The utilization of biomass as a source for the production of NPs has the potential to mitigate issues pertaining to cost, sustainability, and pollution. The utilization of biobased nanomaterials (bio-NMs) sourced from biomass has garnered attention in the field of water purification due to their cost-effectiveness, biocompatibility, and biodegradability. Several research studies have been conducted to efficiently produce NPs (both inorganic and organic) from biomass for applications in wastewater treatment. Biosynthesized materials such as zinc oxide NPs, phytogenic magnetic NPs, biopolymer-coated metal NPs, cellulose nanocrystals, and silver NPs, among others, have demonstrated efficacy in enhancing the process of water purification. The utilization of environmentally friendly NPs presents a viable option for enhancing the efficiency and sustainability of water pollution eradication. The present review delves into the topic of biomass, its origins, and the methods by which it can be transformed into NPs utilizing an environmentally sustainable approach. The present study will examine the utilization of greener NPs in contemporary wastewater and desalination technologies.

■ INTRODUCTION

Given the rapid population increase and ever-increasing needs, the need for pure water is a challenging problem. According to recent surveys, over 1.2 billion people throughout the globe do not have access to safe drinking water.[1] Pesticides, pharmaceuticals, items for personal hygiene, industrial additives, and household waste are just a few of the emerging contaminants discovered in aquatic habitats.[2−5] The current situation of wastewater treatments and desalination looks promising; however, certain barriers must be overcome for commercializing the processes.[6]

In water treatment, membranes are often used to remove pollutants from water depending on features such as charge and size. Many treatments based on membrane technology like ultrafiltration (UF), reverse osmosis (RO), nanofiltration (NF), microfiltration (MF), forward osmosis (FO), electrodialysis (ED), pervaporation (PV), and membrane distillation (MD) are already employed for water purification.[7−9] Other wastewater treatment methods, in addition to membrane technology, include adsorption, activated sludge bioreactors, photocatalysis, and aerobic and anaerobic digestion. Some of these technologies have claimed to have achieved an efficiency of 99% or more but only under ideal operating conditions of pH (neutral), (low/medium ambient) temperature, simple matrices, or low total dissolved solids (TDS) and (reasonable) contaminant concentration.[10] Under industrial conditions, the efficiency drops down. Moreover, these techniques are costly, and the affordable ones create secondary waste.[7−10] Due to these reasons, wastewater purification and water desalination

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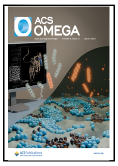

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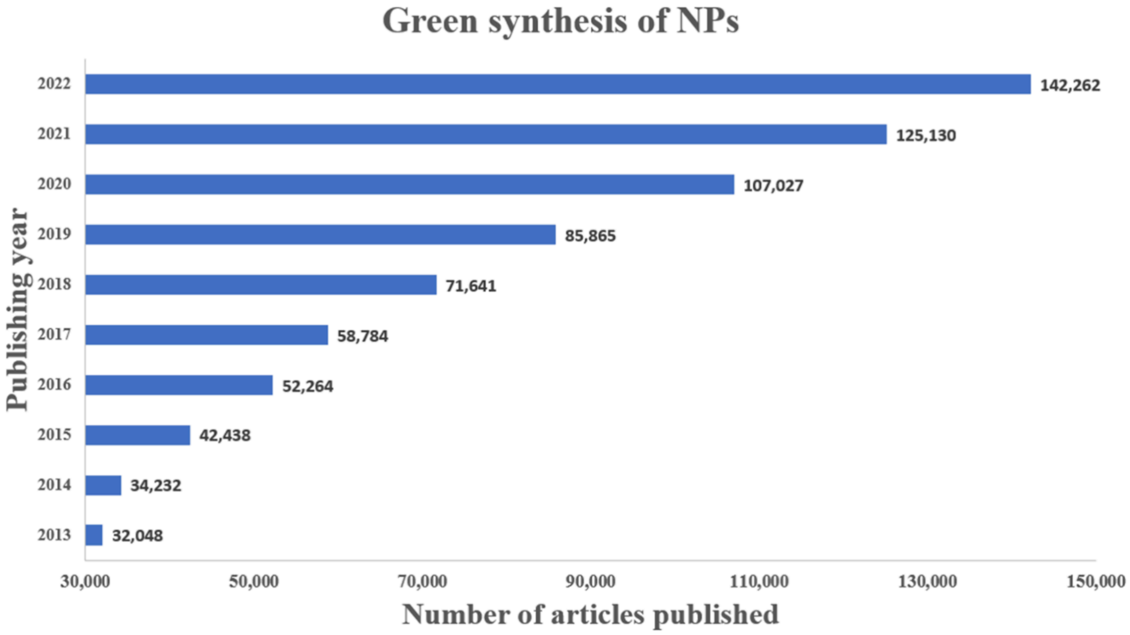

Figure 1. Number of articles published on the green synthesis of NPs from the year 2013 to 2022.

remain challenging, so much so that some developing countries have reached irreversible damage with the availability of clean drinking water. Therefore, a holistic view is required to establish eco-friendly and economical technologies that may avoid future water pollution and surpass wastewater treatment systems' constraints. Considering this idea, using nanomaterials (NMs) stands out among water and wastewater treatment developments with improved efficiency for eliminating contaminants.[10−12]

While nanoparticles are commonly defined as having dimensions between 1 and 100 nm, several studies have reported nanoparticles with sizes exceeding 100 nm. This extended range reflects the diversity in nanoparticle synthesis and application, acknowledging that size alone does not fully dictate nanoparticle behavior or functionality.[12] NMs operate differently than bulk equivalents due to their large surface-area-to-volume ratio and possible quantum effects.[13] While various varieties of NMs are available now, a range of sophisticated forms are expected to be produced in the following years. The US Environmental Protection Agency (EPA) classified NPs into four categories: carbon-based, composites (combining NPs with other NPs or larger, bulk-type material), dendrimers, and metal-based. NMs,[12] in their different constitutions and shapes, can be used for various applications like electronics, energy conservation, biomedicine, textile, food industries, and environmental remediation, including wastewater purification.[14]

NPs hold impressive advantages in wastewater treatments due to their large surface area and their catalytic, optical, electronic, magnetic, hydrophilic, hydrophobic, and antimicrobial properties.[11−13,15] NMs are incorporated into the membrane to increase the efficiency of the water treatment processes. NPs can respond to membrane stimuli, like pH or temperature.[16] This allows for better control over treatment processes. The benefits of embedding the NPs in membranes include increased selectivity, water permeability, mechanical strength, hydrophilicity, and decreased fouling. Moreover, certain NPs contribute antibacterial and catalytic capabilities to the membranes. Metals and metalloids (such as As, Pb, Mo, and others), as well as several hazardous microorganisms and inorganic and organic pollutants, have also been found to be effectively eradicated by the use of various NMs as freestanding NMs or part of the nanocomposite membranes.[12,17,18] Different synthesis methods and experimental conditions can be utilized to customize the characteristics of NPs to specific pollutants to be eliminated. Synthesis of NPs is done broadly by a top-down or bottom-up approach.[19] The top-down method includes chemical or physical synthesis, breaking down the material into its nano size. Physical processes such as evaporation−condensation, milling techniques, laser ablation, and chemical processes like sol−gel and pyrolysis are often used to synthesize the NPs. It offers several advantages, such as precise size, particle shape, surface area, and chemical composition control.[12,13,16] Nevertheless, they have constraints like elevated energy consumption, high prices, and the creation of harmful and destructive waste.[8,20,21]

The bottom-up strategy for creating NPs, on the other hand, involves chemical or biological procedures that build an NM from the molecular level while keeping structural precision.[12,13,16] When NPs are synthesized from biological sources or biomass, they are termed biobased or bio-NPs.[19,22] Biological or thermochemical processes transform biomass resources into sustainable chemicals, fuels, and (nano)-materials. Some biomass sources include agricultural wastes such as rice husk or leaves, animal wastes such as manure or parts of bones from a meat shop, and algae and municipal wastes, to name a few. The conversion of biomass into viable NMs includes using molecular material comprising (wholly or partially) living components, including proteins, antibodies, enzymes, nucleic acids, lipids, viruses, and secondary metabolites.[23−25] Therefore, parts of plants, algae, bacteria, fungi, actinomycetes, and yeasts can produce NPs and act as reducing and stabilizing agents in NP synthesis.[26−28] Each organism may create the same NP content but with different morphologies, sizes, and distributions. In general, biological source type, temperature, pH, reaction medium, solvent, and buffer used for NP dispersion, and surface charge all have an influence on the characteristics of the NPs formed during biosynthetic synthesis. The synthesis of NMs from biological sources is an eco-friendly and nonhazardous process.[26] Moreover, it gives an alternate way to deal with biowaste effectively. These advantages have piqued the scientific and industrial sectors' interest, primarily due to their environmental component. This fact is recognized by the exponentially rising number of published scientific studies which have decided to analyze NPs produced or formed from natural or residual substances (Figure 1).[29]

In this regard, this review aimed to seek current data exhibited in relevant scientific journals on developments in the creation of NMs to treat wastewater and effluents using green synthesis. Detailed analysis of NMs derived from different biomass sources is provided, along with the discussion of current wastewater and desalination membrane technology and how NPs are incorporated into these processes.[30]

■ BIO-NANOMATERIALS

Advancement in NMs and nanotechnology has led to many possibilities in various consumer product fields. NMs have one or more structural dimensions at the nanoscale and have sparked intense scientific interest due to their potential applications in numerous fields of science and industry. NMs are widely used in medicines, food, cosmetics, transport, textile, healthcare, electronics and, in recent years, water purification, to name a few sectors.[12,31−33]

Despite such improvements in NM technology, there is still a paucity of research on the possible effects of NMs on the well-being of humans and the environment. Since NPs may be undetectable after being released into the environment, they may cause a variety of environmental hazards if the cleanup method is inadequate. As a result, further research is required to properly define the structure−function connection of NMs in terms of their underlying chemistry (toxicity and functionality). Additionally, thorough risk assessments must be performed for NMs that pose an actual exposure risk during manufacture or use. Green nanoscience is now advised to reduce the possible health and environmental risks connected with the manufacturing and consumption of NMs and to develop the substitution of current objects with advanced NMs that are more ecologically friendly.[25,26,31,32]

There has been growing interest in NPs for wastewater treatment, especially in developing countries. As the globe confronts a lack of drinkable water, scientists have shown that NMs effectively remove organic pollutants, heavy metals, and even bacteria from the water. They also enhance the efficiency of existing wastewater treatment processes due to their high surface area, strong adsorption properties, strong mechanical stability, high solution mobility, dispersibility, hydrophilicity, and hydrophobicity. Further progress has recently been made in NMs, such as nanophotocatalysts, nanomembranes, and nanosorbents, which might be used to remediate dirty water effectively.[10−13,16,22,26,34]

Biobased NMs are derived from biomass and are a promising alternative to synthetic NMs due to their sustainability, biocompatibility, cost-effectiveness, and biodegradability. Their biocompatibility makes them suitable for medical and biomedical applications. Additionally, their biodegradability and low toxicity make them environmentally friendly, which is helpful for food packaging, agriculture, and water treatment. Finally, they have very high sustainability because of their renewable nature and low environmental footprint. Biobased NMs such as cellulose and its derivatives, chitosan, pure carbon-based NMs like graphene, plain and core−shell silica NPs, and other metal NPs are of interest for wastewater treatment because of their cost-effectiveness and biodegradability.[20,23,25,35] The next section will discuss in detail the sources of biomass, major NMs extracted from biomass, and their synthesis method.

■ BIOMASS PRODUCTION/SOURCES OF WASTE FOR NANOMATERIAL EXTRACTION

Biomass is a sort of renewable biological material that is obtained from plants and animals. In 2020, global biomass production was expected to exceed 130 billion tons annually.[36] The bulk of biomass on land (70−90%) is found in forests; however, the quantity of land biomass is uncertain.[37] Biomass has the potential to contribute to safe and clean renewable energy generation while also supporting the socioeconomic growth of the world.[37] The conversion of biomass to energy is one of the critical factors in reducing the dependence on fossil fuels. Biofuel made from biomass is considered to be a carbon-neutral energy source. Plants, one of the major sources of biomass energy, capture similar amounts of carbon dioxide through photosynthesis while growing as it is released when biomass is burned, making biomass a carbon-neutral energy source.[38] The benefits of biomass are still debated compared with other renewable energy sources. Still, its advantages over fossil fuels are very prominent, mainly due to its renewability, waste reduction capabilities, and reduction in carbon emissions.[38−43]

In theory, burning biomass for energy realizes carbon dioxide in the atmosphere, which is captured by biomass sources, such as trees and crops, during photosynthesis and keeps the carbon dioxide cycle balanced. However, in real life, this process depends on many factors, like harvesting the biomass, regrowing plantation efforts, the type of biomass used, and the energy source it displaces (Figure 2).[44,45]

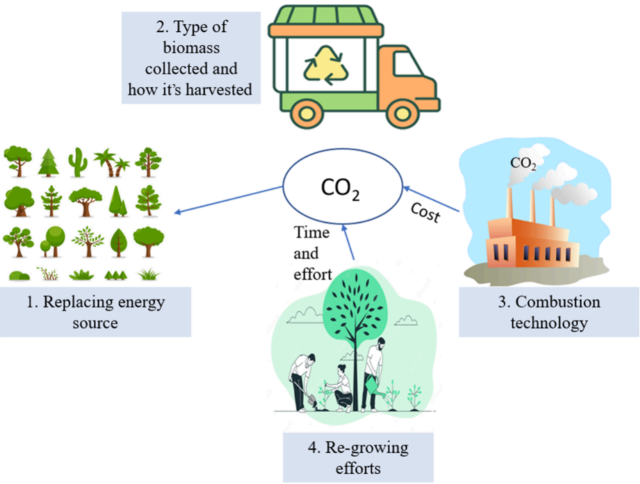

Figure 2. Factors that contribute to carbon-neutral bioenergy.

By biomass management, carbon emissions from the atmosphere may be minimized. Biomass is employed in various applications including water purification, energy sources (heat, electricity, and biofuels), and the manufacturing of green chemicals. Biomass has many supplies and significant reserves and has been extensively developed and exploited.[36] This part of the review examines the alternative use of biomass (besides being a source of biogas) in wastewater treatment procedures. Many compounds may be generated from biomass, including cellulose, chitin, SiO_2 ash, and NPs, activated carbon, keratin, and collagen. These materials have a high potential for utilization in existing wastewater technologies. However, energy costs related with biomass reprocessing and conversion must be considered while assessing its benefits. This technique covers the whole biomass consumption life cycle.

Production of biomass may be ascribed mainly to the following categories.

Agricultural, Wood, and Food Residues. Agricultural residues utilized in renewable energy resources offer a significant potential for expansion in the bioenergy industry in numerous countries (almost 250 mt/yr in Europe).[46] Agricultural leftovers are produced in vast quantities worldwide each year and are mostly ignored. Examples of crop remnants are straw, bagasse, stalk, stem, husk, leaves, shell, peel, pulp, and stubble.[47,48] These residues are either sown into the ground and burned or left to decay before being grazed by cattle. Unused biomass from agricultural sources may be turned into various energy-producing materials, including biofuels (biogas/bioethanol) and energy storage, as well as adsorbent materials in wastewater treatment and desalination membranes.[49,50] Most of the agricultural biomass like rice husk (RH),[51−53] corn cob (CC),[54−56] sugar cane bagasse,[57−60] coconut husks and shells,[61−64] date palm leaves,[65−67] among others, contains organic matter like cellulose, lignin, hemicellulose, graphene (carbon), and inorganic matter, mainly silica (SiO_2). The materials when converted to NMs are widely used in various water treatments.[61,62]

The wood industry generates a lot of trash via various operations. Plywood, construction components, flooring, wood panels, and sawmilling are all examples of waste. Wood biomass is also produced by forest leftovers left over after timber harvesting, plantation thinning, and the extraction of stem wood for pulp and lumber.[68,69] Wood and wood waste accounted for about 5.2% of industrial end use and 4.2% of overall industrial energy consumption in 2021.[69] Waste from the wood industry is also utilized in wastewater treatment procedures as dyes and heavy metal adsorption material.[70−72] Cellulose[69−71] and graphene[73−76] are two significant materials that can be extracted from wood waste for use as NMs in the treatment of wastewater.

The food industry and domestic food waste provide the highest potential biomass energy source residues. Scraps from fruits and vegetables and their oils, filter sludges, coffee grounds, washing and presoaking meat, poultry litter (feathers, manure, water, and spilt feed), the cleaning process of winemaking fibers from sugar, blood and bones from slaughterhouses, and starch extractions are all examples of food industry waste.[77−79] Several techniques may be used to extract many chemical components from food waste. Chitin, cellulose, and keratin are the most important source materials that may be recovered from food and animal wastes for use as NMs in wastewater treatment procedures.[78]

Algae. Algae is common in our aquatic settings and is easily gathered.[80] Algae are photosynthetic eukaryotic creatures that are not commonly considered plants. Single or multicellular organisms containing chlorophyll thrive in water but lack the characteristic stems, leaves, and vascular structures that distinguish plants. Algae have no anthropogenic or negative repercussions, proliferate, and may be farmed in the effluent. Microalgae, macroalgae, and cyanobacteria are all sources of algal production. Microalgae reproduce faster than land crops, and they may thrive on desolate terrain utilizing nonpotable waste and salty water. Using the process of photosynthesis, these organisms synthesize biomass using carbon dioxide and sunlight. This metabolic activity results in the production of many components, such as proteins, carbohydrates, metabolites, and lipids.[80−82]

Algae biomass production focuses on finding and increasing features such as quick growth rate and high oil content that make algae an appealing source for biofuel conversion.[83] Algae can also make biopolymers like cellulose (nano), polyolefins, polyesters, and polyamides as well for use as an aid in the synthesis of several metal-based NPs.[80−82,84,85] Microalgae-based biofuels exhibit superior cost-effectiveness in comparison with other feedstocks. According to Demirbas et al.,[86] microalgae that are capable of photoautotrophy have a better efficiency in converting sunlight into biomass compared to higher plants. Terrestrial plants have a photosynthetic efficiency of less than 4%, while algae possess a range of efficiency between 3 and 9%.[87] The exceptional efficiency in using light is seen in the rapid growth rate of microalgae and the consequent generation of biomass. In addition, it should be noted that algae exhibit a higher degree of tolerance toward fluctuations in light intensity when compared to higher plants.[88,89] This characteristic allows them to effectively sustain themselves through autotrophic means, specifically, by engaging in the process of photosynthesis. Simultaneously, some species of microalgae have the capability to produce a substantial amount of energy-dense molecules via the use of organic carbon sources such as glucose.[90−92]

The vast majority of NPs produced by algae species are also effective bactericides. When it comes to the bioactive molecules used in the synthesis of NPs, algae use the same but somewhat different compounds than other types. Polysaccharides and protein residues in algae can decrease and stabilize NPs.[37,81,85] One significant advantage of using algae is the availability of a broad range of phytochemicals. Some algal species include alkaloids, amino acids, flavonoids, saponins, carbohydrates, tannins, sterols, and phenolic compounds. Once purified, each of the chemicals may further modify the NM's size, shape, and active qualities.[26]

Bacteria and Fungi. Bacteria are the most numerous forms of life. They are unicellular organisms with cell walls but no organelles or an organized nucleus. They inhabit the air, soil, water, and cells of plants and animals. Some bacteria are pathogenic, while others are beneficial. Bacteria recycle the soil's nutrients and assist in digestion.[32] Moreover, several strains, such as *Bacillus subtilis* and *E. coli*, are exceedingly simple to cultivate and have a highly adaptable genetic code. Due to these properties, beneficial bacteria are being used as biomass sources in various wastewater treatments. They can be used for the green production of NMs.[93−95] Apart from the aid in synthesis of metallic NPs,[93,94,96,97] bacteria can produce bacterial cellulose to be used in wastewater treatments.[98−107]

Fungi are eukaryotic creatures that get nourishment by secreting digestive juices into their immediate surroundings and absorbing the dissolved molecules.[94,108−110] As a by-product of large-scale fermentation operations, fungal biomass (FB) is a potential biomass source. Its distinguishing feature is chitin, a long-chain polymer and glucose derivative that strengthens their cell walls.[94,111] Fungi cell walls, besides chitin,[112] may also comprise of polysaccharides like cellulose[31]

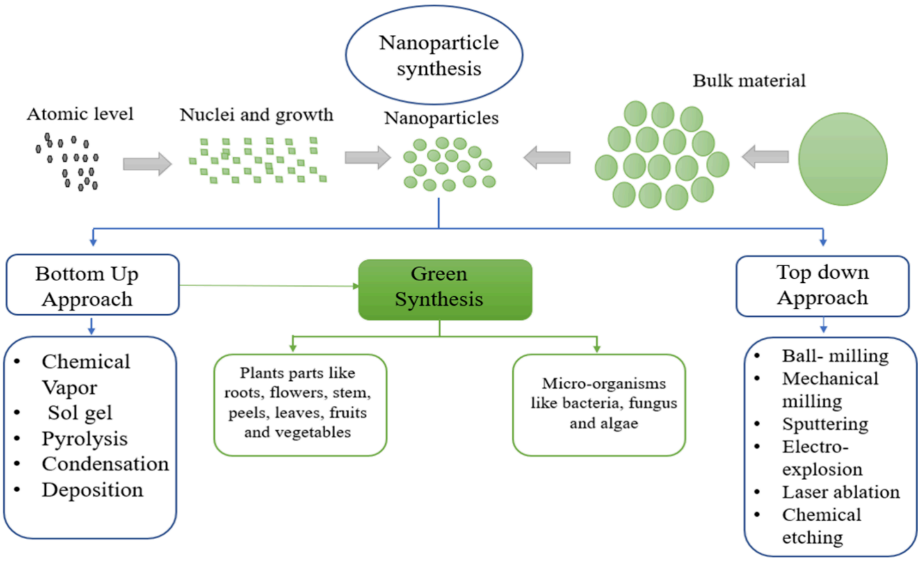

Figure 3. Different methods for NP synthesis.

and facilitate the development of metallic NPs of various forms, sizes, and compositions.[32,109,110,113,114]

A variety of active chemicals found in bacteria and fungi may stabilize NPs. Amino acids from proteins found on the cell wall and within the cytoplasm, like tryptophan and tyrosine, may decrease and stabilize NPs. These acids serve as a protective capping agent, rendering them nontoxic to mammalian cells. Sugars (like aldose and ketose) may also act as reducing/stabilizing agents. These active molecules, found in and on many bacteria species, react with metal ions and reduce them, enabling metal ions to combine with one another and encourage the formation of more structural features, such as NPs of different shapes.[26,94,115,116]

■ NANOPARTICLE SYNTHESIS

The field of NM synthesis has made great strides in recent years, providing more novel pathways to create NPs for applications in multiple fields. NP synthesis is usually done by two approaches, top-down or bottom-up, which are considered traditional approaches (Figure 3).[13,16,23,26,117,118] The top-down approach involves chemical or mechanical disruption of larger particles into smaller components. It entails employing electron beams to etch nanoscopic features onto a substrate, followed by appropriate engraving and deposition methods. Top-down treatments often use physical processes like evaporation−condensation, milling techniques, and laser ablation.[119] It offers several advantages, such as a precise surface area, particle shape, size, and chemical composition control. Regarding drawbacks, the process requires high temperatures and high shear, which might introduce defects and degrade the particles. It can also be costly, especially for smaller volume production.[16,26]

On the other hand, the bottom-up method refers to synthesizing NPs from their atomic or molecular precursors arranged in a predetermined pattern or design.[119] This approach relies on the self-assembly of the ingredients to create the NPs. This process of creating NPs involves a step-by-step assembly in a fixed pattern. The advantages of this approach include great control over the size, shape, and composition of the NPs. Additionally, this approach can create unique structures, which might not be possible with a top-down approach. However, the bottom-up approach is expensive, time-consuming, and unsuitable for large-scale synthesis. Also, the defects in the nanostructures cannot be easily rectified, and most organic solvents used are not considered environmentally friendly.[16,26]

Many traditional NP synthesis methods are energy-consuming and create hazardous wastes. To reduce the environmental burden, researchers have been exploring green synthesis methods for producing NPs. Green synthesis methods aim to reduce the use of toxic chemicals, minimize resource consumption, and reduce the environmental impact. Many green approaches include/propose using green solvents, and bioinspired synthesis, i.e., using biomass as the raw material for NP synthesis.[26,32,118] In recent years, extensive studies on biological systems such as bacteria, fungi, plants residue, algae, and various food wastes has resulted in the transition of biomass into NPs.[47,108]

Using plant (wood and agricultural) and animal leftovers to make NMs is perhaps the most fascinating and ecologically beneficial method of green synthesis.[7,25,32,47,48,70,120] Plants and their components have been the subject of much investigation for NP synthesis owing to the simplicity of scaling up for greater production and being cost-efficient and environmentally benign. Generally, plant or food leftovers are subjected to a technique that extracts particular chemical components from them. The plant or food waste is typically dried, powdered, or fragmented and then subjected to an aqueous extraction process, often involving immersion in hot water, followed by filtration. The extract is then stored at temperatures below 5 °C.[20,32,120] This filtering reagent may include a variety of bioactive compounds depending on the plant or plant matter from which they were extracted. Plant extracts often include various bioactive compounds, such as flavonoids and phenols, although proteins and polysaccharides are also involved in the creation of NPs. These bioactive compounds have functional sections that operate as NP precursor, reducing and stabilizing agents.[25,121]

Use of microbes is another preferred method of generating NPs due to the simplicity of managing biomass and economic feasibility and because they are effective secretors of extracellular enzymes, which leads to large-scale enzyme production.[25,32,82,84,116,122] Many algae species have been found for their ability to catalyze the production of NMs. The generalized procedure to create metallic NMs from various algae species includes drying the samples before being powdered. The fine powder is then mixed with water, incubated for 24 h, and filtered. After filtration, the biomass filtrate is mixed with the NM precursor and left to incubate at room temperature until the color of the solution changes, indicating NM synthesis.[123]

Bacteria synthesize NPs as part of their defensive mechanism.[124] The bacterial cells' resistance to reactive ions in the environment is what causes the formation of NPs. Bacterial cells are often disrupted in high ion concentrations. Their cellular machinery aids in the transformation of reactive ions to stable atoms in order to fight cell death. That are the ions' NPs. This bacterial characteristic is used in the production of NPs. To use bacteria and fungi for NM production, the microbes are first grown aerobically to a suitable optical density, and then the growth medium that holds the cells is blended with the NP precursors. After an incubation time and a perceptible change in media color, the media is agitated at high speeds (>10000 rpm). The NMs are suspended in the supernatant from this spin. The final morphology and NP size are determined by various strains and precursors and interactions with the stabilizing agent present in the bacteria.[26]

The NP synthesis technique from biomass avoids the need for harsh chemicals, which are hazardous to both the user and the environment. Moreover, since the bioactive compounds are extracted using simply hot water, the requirement for high-energy-consuming procedures is avoided. Due to the absence of harsh reagents, the bulk of the NPs produced may be used in biological applications.[20,22,26,32]

■ USE OF BIOBASED NMS AS POTENTIAL MATERIALS FOR WASTEWATER TREATMENTS

The NPs extracted from the biomass can be divided into 6 major categories based on the different sources of waste (as discussed above)—silica (SiO_2)-based NMs, cellulose-based NMs, graphene (carbon)-based NMs, chitosan-based NMs, keratin-based NMs, and other metal-based NMs. This section discusses each of these NP categories and their application in wastewater treatment and desalination.

Cellulose-Based Nanomaterials. Cellulose is often regarded as the most common renewable polymer in the world.[125] RH and other agricultural waste may also produce cellulose, such as sugar cane leaves, date palm leaves, wood pulp, jute, and maise cob.[126−130] It may then be chemically manipulated and turned into different nanocrystals, nanofibers, and aerogels for specialized uses, including water purification.[131]

Cellulose nanocrystals (CNCs) and cellulose nanofibrils (CNFs) are rod-like NPs with lengths ranging from 100 to 2000 nm and diameters ranging from 2 to 20 nm, depending on the cellulose manufacturing technique and origin (Table 1).[132] Nanocellulose is a highly promising material for high-performance membranes and filters that selectively remove impurities from industrial and drinking fluids because of its high strength, chemical inertness, hydrophilic surface chemistry, and large surface area. The defibrillation of cellulose fiber into nanocellulose significantly increases the accessible surface area.[132] This increase in surface area is related to the increased availability of hydroxyl groups on the surface of nanocellulose, where functional groups or molecules can be grafted using methods such as carboxylation, sulfonation, TEMPO-mediated oxidation, phosphorylation, esterification, etherification, silylation, and amidation.[133−137] Metal ions,[138−140] dyes,[141−143] metal,[142,144,145] and microorganisms[142,144] have all been shown to be removed using nanocellulose-based membranes and filters. Oils and cyclohexenes have also been extracted utilizing a modified nanocellulose matrix grafted with hydrophobic or oleophilic functionalities.[146,147]

Table 1. Different Biocellulose-Based NMs Which Have the Potential for Use in Different Water Treatment and Desalination Applications

raw material	NP	shape and size	ref
1. algae, *Cladophora rupestris*	CNC	ND	149
2. pineapple leaf	CNC	*L*, 249.7 ± 51.5 nm; *D* , 4.45 ± 1.41 nm	150
3. softwood pulp	CNF	max *d*, 139 nm	151
4. sugar cane bagasse	CNC	*L*, 250−480 nm; *D*, 20−60 nm	152
5. corn cob	CNC	av *D*, 131.4 nm	153
6. Yeast, *A. xylinum* ATTC 23770	BC		154
7. *A. xylinum* ATCC 10245	BC		155
8. eucalyptus sawdust	CNF		156
9. lime residues	CNF	D: 5−28 nm	157
10. *Gluconacetobacter sacchari*	BC		158
11. coconut husk	CNF	av *D*, 5.6 ± 1.5 nm; *L*, 150−350 nm	159
12. pine needles	CNF	*D*, 30−70 nm	160

Johar et al. synthesized CNCs by sulfuric acid hydrolysis of pure rice husk fibers.[53] Most NPs had diameters and aspect ratios of 15−20 and 10−15 nm, respectively. These CNCs can now be put into various wastewater and desalination treatments. Jackson et al. (2021)[148] were able to impart antibacterial qualities to the surface of a commercial thin film composite (TFC) membrane by employing CNCs collected from the leaves of elephant grass (*Pennisetum purpureum*) that were generated from sustainable sources. TFC membrane surface modification with antimicrobial and needle-like CNC NPs was highly hazardous to bacteria, killing 89% of adherent *E. coli* cells upon contact.

Huang et al. (2019) used CNCs, to effectively manufacture thin-film composite (TFC) nanofiltration membranes (NFMs) (Figure 4).[137] These CNCs enhance the filtering area and

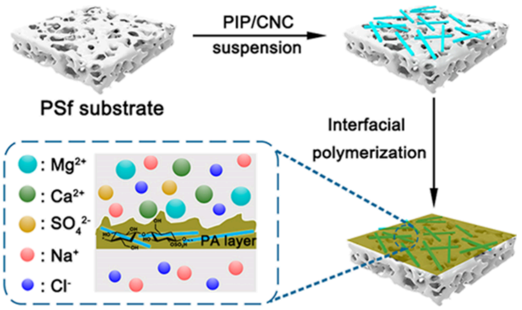

Figure 4. Typical interfacial polymerization is used in the construction of CNCs-filled TFN NFMs, as shown in the schematic. Reprinted with permission from ref 137. Copyright American Chemical Society.

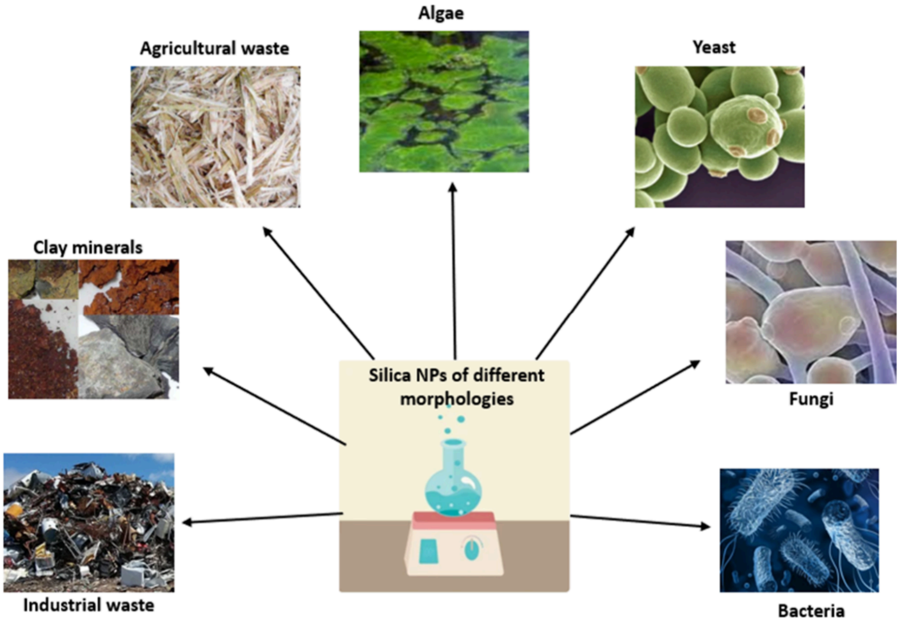

Figure 5. Different biomass sources of silica NPs.

improve the hydrophilic surfaces of the TFN NFMs. The increased filter area, better hydrophilicity, and finer polyamide (PA) selective layer boost the water penetration flux. The hydrophilic CNCs additionally improve the chlorine resistance of the TFN NFMs. This work shows that eco-friendly NMs are excellent nanofillers for synthesizing TFN NFMs with increased water penetration flux without compromising salt rejection.

Silica (SiO_2)-Based Nanomaterials. Silica, commonly known as silicon dioxide (SiO_2), is an attractive material for a range of applications due to its variable and controllable pore size, customizable interface, exceptional mechanical properties, and relatively benign chemical composition.[161] SiO_2 NPs are employed in several applications, including ceramics, chromatography, anticorrosion agents, water purification, and catalysis.[162] The biosources of SiO_2 are considered to be waste materials which include rice husk, peanut shell, bamboo leaves, sugar cane bagasse, algae, bacteria and fungi (Figure 5).[163] During harvest time, the agricultural waste materials are burned to release nutrients for the following growing season and get rid of a vast number of them. During combustion, carbon, oxygen, and hydrogen included in these waste items are transformed into combustible gases including carbon monoxide, hydrogen, methane, and ash. This ash is abundant in silica and carbon, although it has not yet been used to its full potential.

There are several publications in the scientific literature on the use of this material to create high-quality SiO_2 NPs. Using rice husk for the first time, Jansomboon et al. produced silica micro- and NPs.[153] Sachan et al. worked on a comparative investigation of the green synthesis of SiO_2 NPs from leaf biomass and their application to the removal of heavy metals from synthetic wastewater.[164] SiO_2 NPs including adsorbent materials are capable of removing Pb^{2+} and Cu^{2+}. Fahrina et al. developed an antimicrobial polyvinylidene fluoride (PVDF) membrane employing ginger extract-SiO_2 NPs (GE-SiO_2 NPs) for filtering of bovine serum albumin (BSA).[165] GE-SiO_2 NP substances areinvolved in membrane hydrophilicity enhancement and antibiofouling. The antibacterial characteristics of the PVDF/GE-SiO_2 NPs membrane was shown toward *Staphylococcus aureus* and *Escherichia coli*. Using cross-flow filtration, the fouling assessment of BSA content was examined. A satisfactory flux recovery ratio (FRR) of 97.92% was attained.

Due to newly developed technology, it is feasible to manipulate the genetic material of diverse bacteria and yeast, so that they can be utilized for the production of valuable NMs. In fact, they are regarded as the most effective environmentally friendly NM factories.[166] There have been reports of bacteria-assisted SiO_2 NPs production. Using bacterial culture solutions, Vetchinkina et al. synthesized silicon nanospheres varying in size from 5 to 250 nm.[167] Actinobacteria species were used by Singh et al. to manufacture silicon/silica nanocomposites. In this paper, both the silica precursors K_2SiF_6 and microorganisms are discussed. The bacteria's reductase and oxidant enzymes lead to the creation of silica NPs.[168] Zamani et al. used *Saccharomyces cerevisiae* yeast for the biochemical production of silica NPs for better oil recovery applications.[169] It is seen that the majority of the powder is composed of spherical particles, while some particles are hazy and almost shapeless.

Recent years have seen an increase in interest in fungi as source materials for the manufacture of many NPs. The employment of fungi in the manufacture of NPs has the potential to be interesting since they produce vast quantities of enzyme and are easier to work with in the lab. *Fusarium*, *Aspergillus*, and *Penicillium* offer tremendous promise for the extracellular bioproduction of various metal NPs, whereas *Verticillium* Sp. might be collected for intracellular NP synthesis, according to studies. There are several studies in the scientific literature about the synthesis of SiNPs utilizing fungus. Pieła et al. produced silica NPs of specified size and form by bioconverting corn cob husk with the *Fusarium culmorum* fungus.[170] Bansal et al. discovered a novel method for producing nanosilica from rice husk. *Fusarium oxysporum* is employed to bioleach silica from rice husk in this paper. This fungus species is capable of rapidly biotransforming biosilica from rice husk into crystalline silica NPs.[171] Estevez et al.

generated silica NPs by the biodigestion of rice husk utilizing the Californian red worm in intriguing research. Worms are fed rice husk and water, which result in the production of humus. Following various treatments, silica NPs in the range of 55–250 nm are formed.[172]

Silica and hybrid silica-based NMs are the most widely used for water filtration because of their chemical stability, low cost, and relatively easy surface modification.[52] Kumari et al. synthesized SiO_2 NPs from corn cob and mixed zerovalent iron (nZVI) to create nanocomposites.[173] The conjugation with silica matrices inhibited nZVI aggregation, increasing surface area, and permitting effective sorption of the Cr(VI) species to the nZVI surface. Table 2 lists the different bio-SiO_2 based NMs used in different water treatment and desalination applications.

Table 2. Various Biosilica-Based Nanomaterials with Potential for Application in Diverse Water Treatment Processes

raw material	properties	ref
1. stem bark extract of *Syzygium alternifolium*	spherical/34–49 nm	174
2. sugar beet bagasse	spheroid/38–190 nm	175
3. rice straw	discs, *D* 172 nm and width 3.09 nm	176
4. sugar cane bagasse	spherical/30 nm	177
5. fungus *Fusarium oxysporum*	2–5 nm	178
6. *Bambusa vulgaris* leaves	ND	179
7. bacteria, *Actinobacter species*	ND	168
8. *Eisenia fetida*	av *d* 81 nm	180
9. bentonite clay	spherical/98 ± 20 nm	181
10. weed, *Carex riparia*	irregular	182

Carbon-Based Nanomaterials. Carbon quantum dots (CQDs), a novel type of carbon NM, are brilliant photoluminescent quasi-spherical NPs with mostly graphitic sp^2 or sp^3 carbon hybridization and a size of less than 10 nm (Table 3).[172] They involve multiple oxygen-containing functional groups which have attracted a great deal of interest due to their unique properties, such as simple large-scale production, reduced costs, robust chemical stability, simple functionalization, fine particulate sizes, high surface area, low toxicity, and appropriate biocompatibility. Another carbon-based material derived from biomass is graphene. Graphene, a two-dimensional 2-D lattice of sp^2-hybridized carbon, has several unique features and is used in a variety of disciplines.[183,184] Unfortunately, graphene's zero band gap restricts its uses in the optical and photonics fields. The quantum confinement effect might be used to improve the band gap of graphene by reducing its lateral dimensions into quantum dots.[173] Because of its unusual photoluminescence and physicochemical features, graphene quantum dots (GQDs) have received a lot of interest.[185−188] Wang et al. demonstrated a simple one-step one-pot technique for producing GQDs from RH waste.[183] GQDs generated have an average size of around 3.9 nm and 2–3 graphene layers. Under UV light (365 nm), the RH-GQDs were distributed in water and displayed (Figure 6) vivid blue PL. The RH-GQDs quenched Fe^{3+} ions with excellent selectivity, making these GQDs a potential sensor for Fe^{3+}. Meanwhile, the GQD residue can be utilized to make amorphous SiO_2 NPs.

Table 3. Different Biographene-Based NMs Which Have the Potential for Use in Different Water Treatment and Desalination Applications

raw material	properties	ref
1. leaf extracts of neem (*Azadirachta indica*)	GQDs/5 nm	192
2. algae, *Microcystis aeruginosa*	GQDs	193
3. microalgae *Gymnodinium*	GQDs/10 nm	194
4. *Mangifera indica* (mango leaves)	GQDs/2–8 nm	195
5. microalgae, *Chlorella pyrenoidosa*	CQDs	196
6. red algae, *Gracilaria*	GQDs	197
7. orange peels	CQDs/1.16 ± 0.1 nm	198
8. *Catharanthus roseus* (white flowering plant)	CQDs/∼5 nm	199

A carbon quantum-dot-embedded polysulfone (CQDs-PSF) membrane for antibacterial activity in FO was synthesized by Mahat et al.[189] The incorporation of a CQDs-PSF membrane improved the antibacterial performance and hydrophilicity of the membrane for FO. With 1.0% CQDs loaded on a PSF membrane, both the water flow and the reverse salt flux increase, enhancing the membrane's FO performance. The CQD-modified PSF membrane has antibacterial properties against both Gram-positive and Gram-negative microorganisms. Lecaros et al. fabricated tannin-based TFC membranes including nitrogen-doped GQDs for butanol dehydration through pervaporation.[190] The inclusion of NGQDs enhanced the membrane's water permselectivity. The NGQDs impeded the movement of butanol and facilitated the passage of water at a quicker rate. According to Amari et al. the synthesized chitosan/nitrogen doped GQD (CS/NGQD) nanocomposite had greater pollutant removal efficiency than its components, CS and NGQD.[191] This nanocomposite removed 60% of the protein and 88% of the bacterial load. Pharmaceuticals (63% for chlorothiazide, 81% for carbamazepine, and 89% for ranitidine), dyes (82% for Azo blue, 84% for methylene blue, and 94% for orange G), and fluoride (42%) all had a higher removal efficiency. Notably, the CS/NGQD nanocomposite reusability investigation was done for up to five cycles, revealing that the percentage removal of protein, bacteria, medicines, dyes, and fluoride was maintained at acceptable standards with no notable decline in nanocomposite efficiency.

Chitosan-Based Nanomaterials. Chitin is the most common natural amino polysaccharide, generating almost as much as cellulose yearly. It is readily generated from crab or shrimp shells, which are considered food wastes. Deacetylation of chitin (its fully acetylated form), which is found in the cell walls of most fungal biomass (chitosan is found in the cell wall of Mucorales), insect cuticles, and crustacean shells, produces chitosan (Figure 7).[189] Shrimp shells are now the primary source of chitosan for industrial manufacturing. It is biocompatible and nontoxic, with chemical tunability and antimicrobial and antioxidant action.[200,201] It is used in various applications, including but not limited to medicinal aids, molecular sieves, viscosity builders, heavy metal adsorbents, chelating agents, and desalination membranes. Because of the presence of amino groups, this material may be employed immediately in solid form for adsorption applications (complexation of cations or organic molecules, electrostatic attraction or ion exchange in acidic media).[202] It may also be employed in liquid form (dissolved in acidic media) to neutralize charges, coagulate-flocculate anionic species (dissolved materials, colloids, and suspended particles), and complex metal ions.[203]

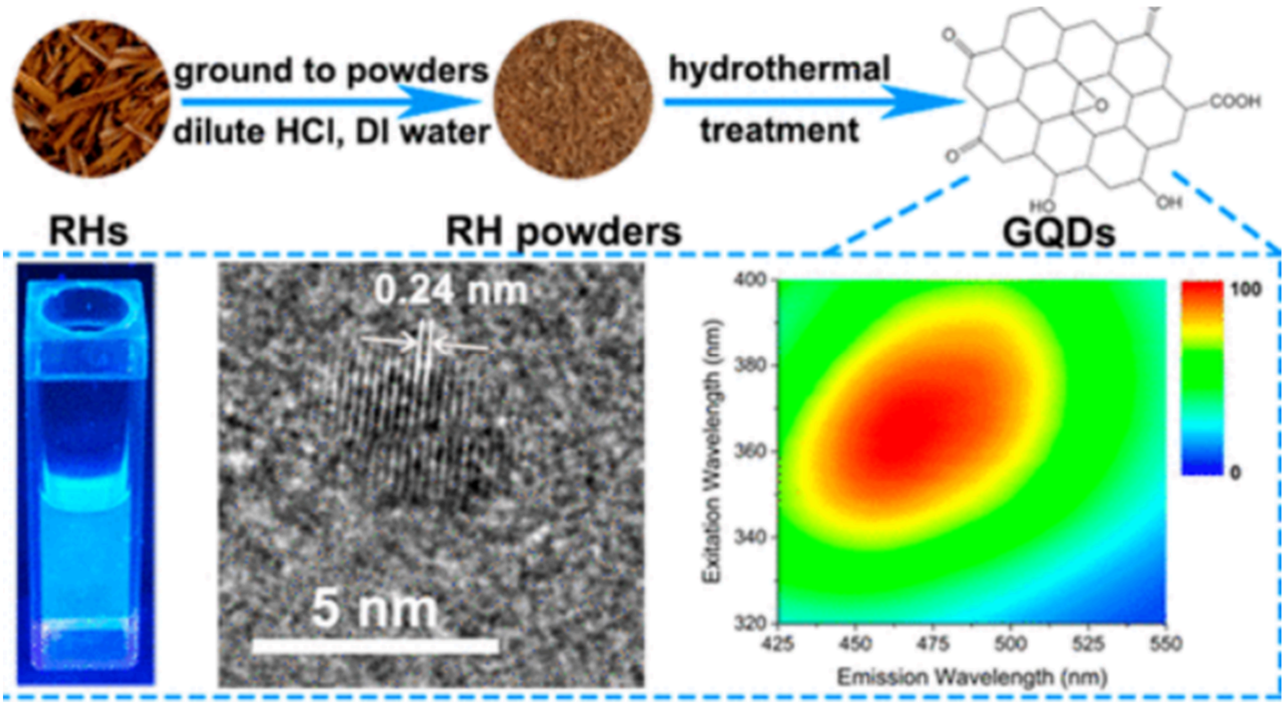

Figure 6. Synthesis process of GH-GQDS with a digital picture of a RH-GQD aqueous dispersion under the irradiation of 365 nm UV light, TEM image, and PL 3D mapping of the RH-GQD aqueous dispersion. Reprinted with permission from ref 177. Copyright AIP.

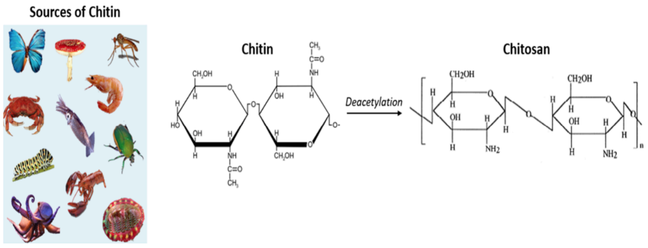

Figure 7. Image showing sources of chitin and chemical structural change during the deacetylation process of chitin to chitosan.

Chitosan, in particular, has been identified as a potential cationic adsorbent for removing anions, heavy metals, poisonous organic dyes, aromatic compounds, oil spills, and pharmaceutical residues.[204−210] Chitosan is an ideal option for adsorbing harmful metal ions from aqueous solutions because it has several chelation sites and amino and hydroxyl groups that bind metal ions through coordination bonds or ion exchange.[211−214] Chitosan is prone to be soluble in acidic conditions and poor mechanical strength, so chitosan is mixed with different materials to create adsorbent materials and membranes for its effective use in wastewater treatment. Several studies have been conducted to assess the adsorption properties of chitosan and its modified forms to use them to remove different heavy metals.[215−218] Omer et al. (2022) discussed the most recent developments in chitosan-based adsorbents and their adsorption abilities toward several harmful heavy metal ions, including As(III), As(V), Cu(II), Cr(VI), Pb(II), and Cd(II), in his 2021 review paper.[204]

The adsorption processes of chitosan and chitosan-based nanocomposite polymeric membranes are critical in providing greater understandings that may improve the efficiency of the membranes for pollutant removal.[219] Shafi et al. extracted multi-ionic electrolytes and *E. coli* from wastewater with a chitosan-based in situ mediated TFC NF membrane.[220] The rejections of Na^+, K^+, Mg^{2+}, Cl^-, and SO_4^{2-} in the permeate of the binary electrolyte solution were reported to be 81, 28, 87, 96, and 98%, respectively, at a maximum water flow of 214 10 L m^2 h^{-1}. The feed solution of *E. coli* rejected 99.9% of *E. coli* after running through the membrane at a water flow of up to 220 L m^2 h^{-1}. Kayani et al. investigated the influence of different amounts of polyethylene glycol and 3-aminopropyltriethoxysilane on the characteristics of chitosan-based RO membranes.[221] The flow and salt rejection values of the hybrid composites rose to a maxima of 80% and 40.4%, respectively, according to permeation measurements. Unlike control membranes, modified films show antibacterial activity against *Escherichia coli*. Kumar et al. discovered that chitosan surface modification with a graphene oxide nanocomposite is an effective adsorbent for As(V).[222] The adsorbent's regeneration capability has been shown using NaOH. Furthermore, the adsorbent stability and regeneration for three effective adsorption−desorption cycles make it an intriguing adsorbent material.

Carbon nanotubes were thought to be excellent materials when combined with chitosan to create an adsorbent membrane for heavy metal removal.[223,224] Particular emphasis is placed on the chitosan/biochar (BS) composite, which was employed to improve the adsorption capacity of the produced polymeric membrane. Biochar has been explored in adsorbent membranes with essential applications, such as the elimination of heavy metals, phosphates, and different antibiotics and medicines from fluids due to its porous structure.

Keratin-Based Nanomaterials. Keratin may be found in feathers, fingernails, hair, animal claws, horns, and wool.[225,226] It is a 19 amino acid protein, and one of the most prevalent fibrous proteins. These amino acid residues are linked by peptide bonds, resulting in a ladder-like structure with tight packing of -helix and -sheet structure.[227] Keratin cysteine residues feature "thiol −SH groups" that cross-link the whole matrix through strong disulfide (−S−S−) linkages. Chicken feathers (CFs) are a natural keratin byproduct of the poultry industry, with over 65 million tons produced yearly. The feathers account for about 4−6% of a mature chicken's total weight. The poultry processing sector in the United States alone produces more than 4 billion pounds of chicken feathers every year. Feathers are robust and light, with a keratin macromolecule content of 91% and an average molecular weight of 10 kDa. They exhibit great tensile strength, structural toughness, and thermodynamic stability with no water solubility over a broad pH range.[225] Poultry feathers are often disposed of in landfills, adding to environmental pressures. Researchers have modified keratin for possible use as a biosorbent for water filtration.[228,229]

Sun et al. used several ways to remove Cr metal from the CFs.[230] Initially, CFs were treated with an aqueous solution of NaOH, which caused the keratin protein on the feather surface to exfoliate. The keratin protein was cross-linked with epichlorohydrin before being functionally enhanced with ethylenediamine. Metal absorption was 30.5% in raw CFs, 43.8% in NaOH-treated CFs, 44.2−81.4% in epichlorohydrin CFs, and 90% in ethylenediamine-epichlorohydrin CFs. Khosa et al. investigated the removal of As metal integrated into CFs by two distinct chemical routes.[231] They unfolded keratinous protein and revealed distinct functional groups with increased functioning (−COOH, $-NH_2$, and −S−S−). The CF-modified methyl alcohol proved to have the maximum arsenic uptake in the 85−90% range. As a result, the carboxylic group in modified CF was discovered as an excellent activator of arsenic absorption, resulting in efficient esterification.

Ganesan et al. developed a novel carbon-based molybdenum oxide nanocomposite (MoO_3-KSC) from keratinous sludge utilizing CF waste as a keratin source and $(NH_4)_6Mo_7O_{24}$ as a precursor carbonization catalyst.[232] The generated MoO_3-KSC nanocomposite produced possessed a significant aggregation surface area, a high crystalline structure, and a high porosity, suggesting a strong electrochemical reaction. The obtained MoO_3-KSC was utilized to fabricate a plated screen-printed carbon electrode (SPE) for the detection of hydroquinone (HQ) and catechol (CC) in ambient fluids. The electrocatalytic capability of MoO_3-KSC/SPE functionalization surpasses that of bare SPE and KSC/SPE for HQ and CC detection. As a result, by utilizing the differential pulse voltammetry approach, the MoO_3-KSC/SPE NM modified electrode has good sensitivity and selectivity for determining HQ and CC in ambient fluids. The manufactured MoO_3-KSC/SPE NM modified electrode was also used to determine ambient water samples, and the results were satisfactory.

Metal-Based Nanomaterials. Biological systems, such as plants, bacteria, algae, fungi, and yeasts, have been found to manufacture a wide variety of metal and metal oxide NPs (Table 4).[233] This section highlights the importance of green synthesis techniques for producing metal oxide NPs, such as Au, Se, Zn, Co, Ag, Cu, Ti, and Ni, among others. Several promising green NMs, photon nanocatalysts, metallic NMs, and metal oxide NPs have been widely shown to have antibacterial properties. Silver NPs (AgNPs) have an average size of 1−40 nm and serve as antibiotics, antimicrobials, and antifungal agents. AgNPs have a bactericidal action. They first generate free radicals, which cling to and destroy the bacterial cell wall. They are linked with bacterial DNA after breaking the cell wall, changing the cell membrane characteristics, and denature the enzymes. AgNPs play an important role in wastewater treatment by rapidly inactivating microbial cells and minimizing membrane biofouling.[234] In general, AgNPs have good antibacterial activities against a broad range of pathogens, including bacteria, fungi, and viruses. Plants include reducing and stabilizing substances that aid in the synthesis of biocompatible AgNPs. Secondary metabolites found in the extract, such as alkaloids, phenols, terpenoids, flavonoids, proteins, and carbohydrates, operate as reducing agents.[235]

Table 4. Different Bio-Metal-Based NMs Which Have the Potential for Use in Different Water Treatments

raw material	metal NP	rroperties	ref
1. algae, *Gracilaria corticata*	Ag	spherical/18−46 nm	255
2. peel, *Punica granatum*	ZnO	118 nm	256
3. algae, *Padina gymnospora*	Au	spherical/53−67	257
4. fruits, *Vitis rotundifolia*	CoO	ND	258
5. seed, *Lactuca serriols*	NiO	ND	259
6. fungus, *Yarrowia lipolytica*	Au	triangles/15 nm	260
7. bacteria, *Azoarcus* sp. CIB	Se	ND/123 ± 35 nm	261
8. seed, *Terminalia chebula*	Fe_3O_4	ND	256
9. algae, *Plectonema boryanum*	Pt	spherical/30−0.3 μm	262
10. *Fusarium oxysporum*	CdS	5−20 nm	263

Minhas et al. investigated the antibacterial activities of polysulfone (PS) composite membranes utilizing biogenic silver NPs generated from *Cladophora glomerata* (L.) Kütz and *Ulva compressa* (L.) Kütz extracts by a spin-coating technique.[236] The capacity of Ag-NPs/PS composite membranes from algae to exhibit exceptional antibacterial activity against all bacteria, including *K. pneumonia*, *P. aeruginosa*, *E. coli*, *E. faecium*, and *S. aureus*, was examined. Moodley et al. focused on the green synthesis of Ag NPs from fresh and freeze-dried leaf *Moringa oleifera* extracts and their antibacterial properties.[237] In addition, X-ray diffraction examination revealed that the size distribution of Ag NPs in both samples had mean diameters of 9 and 11 nm, respectively. Antimicrobial activity was shown by silver NPs against both strains of bacteria and fungi.

Nanocatalysts including semiconductor materials, zero-valence metals, and bimetallic NPs may degrade organic pollutants such as PCBs, insecticides, and azo dyes. TiO_2 NPs are the most important photocatalysts for water purification. TiO_2 NPs created very reactive oxidants, such as OH radicals, which have disinfection characteristics against harmful microbes. Nitrogen-doped TiO_2 NP catalysts and TiO_2 nanocomposites containing multiwalled carbon nanotubes reduced microbiological pollutants in water successfully.[238,239] The manufacture of anatase TiO_2 NPs used a low-cost titanium oxysulfate with polyvinylpyrrolidone as a capping agent. These green-synthesized TiO_2 NPs were more effective, degrading 94% of methyl orange in 150 min under UV light, compared to a commonly produced TiO_2 that degraded 20% faster.[240] A straightforward solvent-free green chemistry technique using titanium tetraisopropoxide as a precursor and soluble starch as the template was used to synthesize an eco-friendly visible light active mesoporous anatase TiO_2.[241] These TiO_2 NPs outperformed methylene blue photocatalysis, which may be attributed to their increased surface area (87.2 $m^2\ g^{-1}$) and the self-doping of TiO_2. Moreover, they are reusable and extremely resistant to photodegradation, with the degradation efficiency lowered by just 13.3% at the conclusion of 10 cycles (87.3%). Shen et al. showed photocatalytic activity of biologically synthesized cerium-doped TiO_2 NPs mounted on porous glass for the degradation of methyl orange (rate constant 0.095 min^{-1}) and rhodamine B (0.23 min^{-1}) under visible light (band gap was 2.8 eV).[242]

ZnO NPs can also have photocatlytic properties. *Corymbia citriodora* leaf extract was employed for the biosynthetic pathway of ZnO NPs, and under visual irradiation, 84% of methylene blue was destroyed after 90 min.[243] As compared to hydrothermally synthesized ZnO NPs, which exhibited only 60% degradation, these biosynthesized NPs had a band gap that was lowered to 3.07 eV, resulting in better photocatalytic activity under visible light. In another investigation, photocatalytic degradation of more than 56% was reported under sunshine within 6 h using ZnO NPs biosynthesized using grapefruit peel extract *Citrus paradisi*.[244] Darroudi et al. studied the sol−gel synthesis, characterization, and neurotoxicity of NPs of ZnO utilizing gum tragacanth.[245] At varying calcination temperatures, spherical ZnO NPs were produced.

Magnesium oxide embedded nitrogen self-doped biochar composites (MgO@Nbiochar) for rapid and high-efficiency heavy metal adsorption in an aqueous solution were developed by Ling et al.[246] The research found that MgO@Nbiochar had a good adsorption performance toward Pb, which might be due to interactions between multiple functional groups on MgO@N-biochar and Pb or Cd ions. Surface adsorption and ion-exchange interactions were also crucial in Pb adsorption. These findings imply that designing surface functional groups might be a more viable strategy for high performance adsorbents against heavy metals.

As compared with bulk materials, iron oxide NPs (FeNPs) have superior characteristics for the elimination of organic pollutants. Notably, their magnetic or ferromagnetic capabilities render them particularly valuable in separation procedures.[247] Certain FeNPs, especially those exhibiting a core−shell configuration, offer the potential to improve their magnetic characteristics to a greater extent.[248,249] FeNPs (Fe_2O_3 and Fe_3O_4) are capable of removing heavy elements like arsenic. The colored humic acids in wastewater were successfully removed by Fe_2O_3 NPs.[250] The polymer-grafted Fe_2O_3 nanocomposite efficiently removes divalent heavy metal ions such as copper, nickel, and cobalt across a wide pH range of 3−7. Cai et al. investigated the adsorption of Cu^{2+} ions in aqueous solution by a composite of montmorillonite and biochar.[251] The adsorption of Cu^{2+} ions from an aqueous solution by the composite was thoroughly investigated. The composite was shown to be a mesoporous material. The surface of the montmorillonite-biochar composite is rough, and the layer structure is uneven. Adsorption was also confirmed to be accomplished in comparatively brief time periods.

Zerovalent iron NPs effectively convert chlorinated organic molecules and PCBs. Wang et al. investigated the activation of persulfate by green nanozerovalent iron-loaded biochar (nZVI-BC) for *p*-nitrophenol elimination.[252] In comparison to C-nZVI-BC, G-nZVI-BC included tea polyphenols, which enhanced Fe^0 dispersibility on BC, inhibited nZVI agglomeration on BC, and accelerated PNP degradation significantly. The G-nZVI-BC/PDS system effectively removed PNP in the pH range of 3.06−9.23. The reusability of G-nZVI-BC and the PNP elimination impact in real water bodies suggested that G-nZVI-BC has a promising future in water treatment. The Cu/sodium borosilicate nanocomposite was created by Nasrollahzadeh et al. utilizing *Acalypha indica* L. leaf extract.[253] The research demonstrated a decrease in the concentrations of nitroarenes and organic dyes in water. Parial and Pal reported extracellular production of Au NPs from *Lyngbya majuscula* and *Spirulina subsalsa*, where progressive development of color provided a handy time-dependent visual signal showing large bioconversion of Au^{3+} to Au^0 resulting in a steady synthesis of Au-NPs.[254]

APPLICATION OF BIONANOMATERIALS FOR WASTEWATER TREATMENT TECHNOLOGIES

Green NMs such as nanowires, nanotubes, films, particles, quantum dots, and colloids are used in wastewater treatment systems. Pollutants are eliminated from industrial effluents, surface water, groundwater, and drinking water using NMs in environmentally benign and cost-effective ways.

When examining the use of biobased NMs in wastewater treatment systems, it is important to recognize their distinct advantages and disadvantages. These NPs are very effective in effectively eliminating a broad spectrum of pollutants because of their high reactivity and large surface area. As a result, they are very efficient in processing complex industrial waste and improving the filtration of drinking water. Nevertheless, the implementation of NPs faces challenges such as the possibility of environmental hazards due to NP discharge, the complexities in managing and retrieving these materials, and the need for more investigation to fully understand their enduring effects on ecosystems and the well-being of people.

Originally, three kinds of membrane separation systems were used in water purification systems: RO, UF, and MF. The membrane filtration system is widely used to purify drinking water from wastewater, ocean, and surface water. The use of NPs in filter membranes is now quite common in the area of water treatment systems. In the water treatment system, the NPs performed a variety of functions, such as pollutant material degradation, inorganic material remediation, antibacterial activity, and disinfection. A variety of well-known NPs, including silver NPs, gold NPs, zinc oxide NPs, titanium dioxide NPs, magnesium oxide, and carbon nanotubes, are effectively used in water and wastewater disinfection.[264,265] The zinc oxide NPs have a high potential to destroy harmful microorganisms and may be used instead of UV disinfection to enhance water quality. Pd NPs and silver-based nanocatalysts have improved halogenated organic compound biodegradation and degraded organic dyes.[266−268] Magnetic NPs, carbon nanotubes, metal NPs, quantum dots, and dye-doped NPs are widely used in pathogen tracking. NMs are distinguished by their tiny size and vast surface area, as well as their superior adsorption qualities and strong reduction capacity; these distinguishing traits help to the removal of toxins from wastewater.[269] The use of green NMs for water and wastewater treatment is divided into three categories: (1) nanoscale filtration, (2) pollutant adsorption on NPs, and (3) contaminant breakdown by the NP catalyst.

Nanoscale Filtration Technique. The nanomembranes are composed of nanofibers that are used to remove nanomicrosized contaminants from water bodies in order to prevent fouling.[270] NMs are used to create multifunctional advance membranes, and an inorganic membrane is referred to as a nanocomposite.[271] In UF or RO, nanomembranes are used as a pretreatment measure. NPs such as alumina, silica, zeolite, and TiO_2 are introduced into polymeric UF membranes, where they improve the membrane performance in terms of surface hydrophilicity, water permeability, and fouling resistance. For the reductive degradation of chlorinated chemicals, titanium dioxide NPs with inorganic membranes are used.[272] Silver NPs comprising polymeric membranes significantly prevented the growth of bacterial biofilms on the membrane, which is widely used for water disinfection.

Adsorption of Pollutants on NPs. NMs have the capacity to adsorb contaminants from water, with the surface of the adsorbing material possessing certain functional groups that interact with the contaminant's ionic groups. Adsorbents are composed of NMs or nanostructured materials with extremely high specific surface areas, which may be paired with functional groups, short diffusion distances, specified pore sizes, and surface chemistry.[273] Manganese oxide, zinc oxide, magnesium oxide, titanium oxide, ferric oxides, and carbon nanotubes are extensively utilized NPs for pollutant adsorption.[274] However, it is important to acknowledge that the efficiency of these NP-based solutions is not only defined by their remediation percentage. The cost, recoverability, and reusability of NPs are essential factors for evaluating their efficacy and long-term viability.

Breakdown of Contaminants by NP Catalysts. The nanocatalysts are efficient in the elimination of a pollutant from wastewater due to certain specific properties. Not only may catalytic NPs remove pollutants but they may also break down chemically.[275] Catalytic NPs quickly break down water pollutants such as organochlorine-based pesticides, halogenated herbicides, Azo dyes, polychlorinated biphenyls, and nitro-aromatic compounds. In wastewater treatment systems, nanocatalytic materials, such as zerovalent metallic NPs, semiconductor NPs, and bimetallic NPs, are often employed. Magnetic NPs are specifically used to remove metallic salts, heavy metals, and other organic pollutants from bodies of water.[276] Moreover, the addition of a magnetic core in these NPs offers an additional benefit of facilitating their retrieval from liquid media, hence elevating the practicality of their reutilization in water treatment.

Using the aforementioned categories of wastewater treatment by green NPs, they can used for disinfection, heavy metal removal, removal of organic contaminants, and desalination. Microorganisms, natural organic debris, and biological toxins are regarded as pollutants in excess amounts in water.

Application of Bio-NMs in Wastewater Pretreatment. Wastewater is first treated by multiple pretreatments to make it ready for specific application treatments.[7] The primary challenge associated with wastewater treatment is the accumulation of pollutants in water or wastewater technology. The treatment requires an understanding of the pollutants present and their effects on the environment. Multiple processes are involved in the wastewater pretreatment like pumping, screening, pH adjustments, coagulation and flocculation, sedimentation, dissolved air flotation (DAF), filtration, and prechlorination. Among the methods mentioned above, coagulation and flocculation are the most commonly employed processes that make use of NMs.

Coagulation and Flocculation. Coagulation neutralizes the charges on the particles, and flocculants help them bind together, making them aggregate so they can easily be separated from the liquid.[277] These processes involve the addition of specific chemicals to eliminate the suspended contaminants in water. The contaminants may be organic, like algae, bacteria, viruses, or other organic matter, or inorganic, such as clay and silt. These contaminants contribute to the water's turbidity and should be reduced. Inorganic coagulants such as aluminum and iron salts are considered excellent coagulant and flocculation agents. They are known to neutralize the contaminant particles in seconds, precipitating as metal hydroxides when reacting with water.[277−280]

NMs are becoming more popular as flocculants because of their large surface area, high porosity, mechanical strength, chemical reactivity, and large capacity for adsorption.[281] Sun and colleagues synthesized pure CNCs from cotton pulp. Heavily charged CNCs shown considerable promise as a revolutionary microalgal flocculant.[282] Between pH 4 and 11, the functionalized CNCs exhibited a positive surface charge. The dosage-dependent flocculation effectiveness was dependent on the degree of substitution of the pyridinium moieties. At a dose of 0.1 g, the flocculation effectiveness of cationic CNCs was more than 95%. The CNCs were largely immune to algal organic matter influence. Pb adsorption with sulfonated CNC (bleached birch chemical wood pulp) was investigated by Suopajärvi et al.[283] Comparable to commercial adsorbent capabilities, the adsorption capacity of the NM (in municipal wastewater) was 1.2 mmol/g at pH 5. The increasing lignin concentration boosted the sulfonated adsorbent's adsorption effectiveness. It was able to remove 80% of the solution's turbidity and 60% of its COD content. Liu et al. investigated the flocculation performance of CNC, GO, and polyacrylamide (PAM) on methylene blue in aqueous phase.[284] They observed that GO was the most effective in removing MB, followed by PAM and SWCNTs. According to their findings, electrostatic and also other noncovalent interactions between MB and GO are weak. This proposal contradicted the notion that electrostatic attraction may be responsible for the interaction between GO and MB molecules, which had been the subject of previous speculation. SWCNTs were found to be the poorest flocculation agent to remove MB from aqueous solution, as no apparent floc developed at any pH value. This was due to the limited solubility of SWCNTs in water, which resulted in a weak contact between SWCNTs and the MB.

■ ADVANTAGES AND DISADVANTAGES

Biowaste-based nanomaterials represent a groundbreaking shift toward sustainable wastewater treatment methodologies, intertwining the goals of environmental conservation with technological innovation.[285] Leveraging abundant and often underutilized organic waste from agricultural, industrial, and municipal sources, these nanomaterials offer a cost-effective and environmentally friendly alternative to traditional treatment options. Their nanoscale dimensions afford them a high surface area-to-volume ratio,[285] significantly enhancing their reactivity and efficiency in removing a wide array of pollutants, from heavy metals to organic contaminants.[286] Furthermore, the utilization of biowaste not only diverts it from landfills, thereby reducing environmental burden, but also aligns with circular economy principles by transforming waste into valuable resources. This approach not only addresses pressing waste management issues but also propels wastewater treatment into a new era of efficiency and sustainability, promising cleaner water bodies and a healthier environment.[287]

While biowaste-based nanomaterials present a promising avenue for sustainable wastewater treatment, they are not without their disadvantages.[288] Environmental concerns top the list, as the long-term impacts of these nanomaterials are still largely unknown, raising questions about their potential toxicity to aquatic life and broader ecosystems.[288,289] The challenges extend to the recovery and recycling of these materials after treatment, which can be both complex and

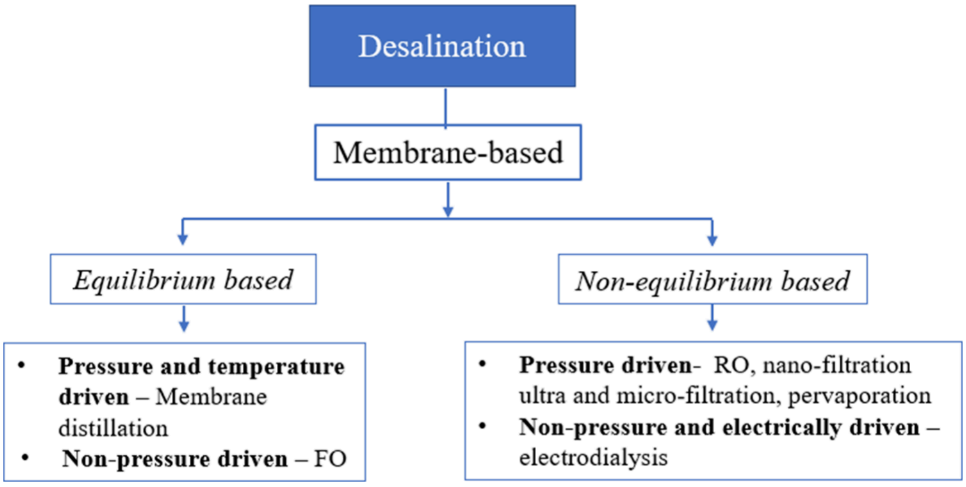

Figure 8. Different membrane-based desalination techniques.

costly, potentially offsetting their initial cost-effectiveness. Scalability is another critical issue, as producing these nanomaterials in quantities sufficient for industrial applications may face hurdles related to feedstock variability and the need for specialized processing equipment.[290] Furthermore, regulatory and safety concerns for workers and the environment necessitate comprehensive risk assessments and the development of new safety protocols, adding layers of complexity and expense. Technical limitations also exist; biowaste-based nanomaterials might not be effective against all pollutants, and their performance can be influenced by factors, such as water chemistry. Lastly, the disposal of these nanomaterials poses its own set of environmental risks, necessitating the development of responsible end-of-life management strategies to ensure that the benefits of these innovative materials do not come at too great an environmental cost.[291]

Application of Bio-NMs in Desalination Technology.

Desalination removes salts from water to make it usable for various applications, including industries, drinking, and agriculture. Desalination can be done by various processes, the majority of which are membrane processes. They are subdivided into equilibrium- or nonequilibrium-based techniques (Figure 8). This section discusses all of the available membrane desalination processes and the recent advances in the field using green NMs.

Membrane Distillation (MD). Membrane distillation (MD) is a temperature-driven separation method that can contribute to lowering our society's water-energy stress.[292] MD is a liquid separation process where a microporous hydrophobic membrane separates the two aqueous solutions at different temperatures—the temperature gradient on the membrane results in a vapor pressure difference.[292,293] The process may be powered by low-grade heat and/or waste at the same time, such as solar energy,[294] geothermal energy,[295] wind, tidal, and nuclear energy, or low-temperature industrial streams.[296] In comparison to other traditional membrane separation systems, the MD separation process offers numerous advantages, including low operating temperatures, cost-effectiveness through the use of waste heat and renewable energy sources, the capacity to process wastewater with an elevated level of purity, and a lower likelihood of membrane fouling.[297−299] As a result of these outstanding characteristics, MD is an appealing technology for wastewater treatment, saltwater desalination, and a variety of other industrial applications such as environmental purification, the food industry,[300] medicine,[301,302] and acid manufacturing, among others.

Much research has been performed to solve the problems related with membrane flow, fouling, wetting, and porosity by modifying MD membranes using NPs such as CNTs, Ag, SiO_2, and TiO_2.[303] Yan et al. developed a highly hydrophobic electrospun NF membrane covered with a network of CNTs for membrane distillation using a spraying approach.[304] The CNT network greatly improved the membrane hydrophobicity and liquid entry pressure. The vacuum membrane distillation (VMD) findings show that CNT-covered membranes performed better in antiwetting and water flux in the desalination process. Hubadillah and colleagues conducted a study wherein they synthesized a ceramic hollow fiber membrane made from green silica for the purpose of seawater desalination using a direct contact membrane distillation (DCMD) technique.[305] The source material for the membrane was rice husk. The permeate flux of DCMD was found to be 38.2 $kg/(m^2\ h)$, which is high. The green ceramic membranes were able to achieve a salt rejection rate of up to 99.9%. Nthunya et al. conducted a study wherein they produced an increased flux in DCMD through the utilization of superhydrophobic PVDF nanofiber membranes that were incorporated with SiO_2 NPs that were organically modified with excess apple extract.[306] The membranes that were integrated with SiO_2 NPs modified with ODTS exhibited the highest level of efficiency. They were able to reject salts at a rate exceeding 99.9% with water fluxes of approximately 34.2 LMH at a temperature of 60 °C. This suggests that they have the potential to be utilized as an energy-efficient method for generating water of high purity.

Forward Osmosis (FO). FO, another membrane technology, has the ability to clean wastewater and provide high-quality water. FO is a technical word for the natural process of osmosis, which involves the movement of water molecules through a semipermeable membrane.[307] In contrast to pressure-driven membrane activities, the osmotic pressure differential drives water transport. This might be the most significant advantage of FO over existing pressure-driven membrane technologies: the elimination of high hydraulic pressure and low fouling tendency. It, therefore, provides an opportunity to reduce energy consumption and membrane replacement cost.[307]

The use of a FO-NF hybrid process instead of a standalone RO unit in brackish water desalination resulted in reduced contamination in the NF and a high water recovery (>90%) owing to the inclusion of the FO phase. Wu et al. created a functional TFC-FO membrane by integrating biogenic silver NPs (BioAg) into a FO membrane's polysulfone (PSf) substrate utilizing *Lactobacillus fermentum* LMG 8900 as the reducing agent.[308] Prior to the phase inversion procedure, the BioAg was inserted in the PSf casting solution. The results showed that BioAg-FO nanocomposite membranes had increased porosity, enhanced surface hydrophilicity, and reduced internalized concentration polarization, resulting in 2.5−4.4 times higher water flow than virgin FO membranes. The antifouling and antibacterial properties of the BioAg-FO membrane were also dramatically enhanced.

Doshi et al. conducted research on the bioroute production of carbon quantum dots (CQDs) from tulsi leaves and their use as a draw solution in FO.[309] In this study, the authors prepared a 5% concentration solution using one-pot hydrothermally synthesized CQDs from tulsi leaves. In FO operation, this innovative draw solution resulted in increased water flow (10.72 L m^{-2} h^{-1}) and reduced RSF (0.03 g^{-2} h^{-1}) using DI water as input compared with 1 M NaCl. In addition, using synthetic wastewater, TCQD-G provided the highest water flow, 5.34 L m^{-2} h^{-1}. DashtArzhandi et al. sought to improve the FO membrane's desalination performance by using green nanocrystalline cellulose (NCC) and halloysite nanofillers.[310] In terms of FO test findings, TFN membranes containing NCC performed better than TFN membranes without NPs, independent of membrane orientations and feed/draw solution concentration. The membranes' solute reverse diffusional fluxes similarly exhibited insignificant variation, and TFN 0.05 was the membrane with the highest performance for both the FO water flow and low solute flux. This was most likely due to the membranes' very hydrophilic surface after inclusion of NCC NPs. Zufia-Rivas et al. investigated the impact of sodium polyacrylate (PAANa) on magnetite NPs generated by green chemistry approaches and their use in FO.[311] In this study, the optimum compromise option for the system Fe_3O_4/PAANa was determined to be the nanocomposite, which exhibits an excellent magnetic response, >25 A m^2/kg, superparamagnetic and hence reversible behavior, and a reasonably high osmotic pressure of 11 bar at high concentration.

Reverse Osmosis (RO). RO is one of the most common and effective processes of membrane desalination technology to purify seawater and brackish water.[312] It has been employed as an alternate source for creating clean water in order to reduce desalination-related expenditures.[313−315] Pressure is applied to a saline solution, which drives the pure water through a semipermeable membrane, leaving the unwanted salts or contaminants passed in the reject stream. The final product or permeate is much purer than the original feedwater. It can also reject proteins, particles, bacteria, sugar, and dyes with a molecular weight greater than a range of 150−250 kDa. The only thing to remember with the RO process is that the pressure applied on the saline solution should be higher than the osmotic pressure of the feedwater to prevent the pure water from moving into the saline solution.[316−319]

While it is true that RO is a well-known and commonly utilized water desalination method, substantial research and innovation are presently underway to overcome the primary issues that the desalination process faces. The most difficult obstacles are RO membrane fouling and salt rejection capacity. Recent work on new membrane fabrication and membrane modification have attempted to improve membrane fouling resistance.[316−318,320] Nevertheless, the use of such membranes outside of the laboratory has to be investigated.

Very significant progress has been made in the development of ultrapermeable and antifouling membranes. Most of the exciting development is being driven by the recent discovery of potential new desalination materials.[321] Among these are aquaporin proteins[322,323] and carbon-based NMs such as carbon nanotubes[324] and graphene-based NMs.[325,326] These innovative materials provide new possibilities for developing next-generation RO membranes. Water molecules are transferred through biological cells by a set of transmembrane proteins called aquaporins (APQs), which offer a suitable solution for desalination. AQPs, which have water transport channels shaped like an hourglass, are very effective at transporting water molecules with excellent selectivity.[327] Aquaporin Z (AqpZ, an AQP present in *Escherichia coli* cells) is more widely employed for membrane production, owing to its ease of harvesting and extraction. Carbon-based materials (CBMs), such as carbon nanotubes (CNTs),[328−331] nanoporous graphene (NPG),[332,333] and graphene oxide (GO),[334,335] have also emerged as potential membrane materials due to their outstanding water transport capabilities. The current body of research on the convergence of biogenic NPs and their application in RO is severely restricted. Thus, further research and investigation are required on the matter.

Nanofiltration (NF). NF is another pressure-driven membrane liquid-separation technology. This process lies between UF and RO. The term NF means the predicted pore size of a membrane that has been defined by molecular weight removal. The intake stream is separated into two parts: permeate, that is the filtered component, and retentate, which is the discarded nonfiltered part. NF has shown good organic material removal.[336,337] NF provides high rejection of multivalent ions like Ca^{2+} and low rejection of monovalent ions, like Cl^-, reducing the water's hardness. The pore size of NF membranes is slightly larger than that of RO membranes, ranging from 1 to 10 nm and operating pressures of 5−35 bar.[338] The membranes are made from polymers, ceramics, and hybrids of polymers and ceramics.[339] The enhanced flux, the wider membrane pores, and less retention are some advantages of NP membranes. Nevertheless, chlorine disinfection is crucial for the elimination of microbial growth that has been recorded in NF distribution networks. To limit microbial development, NF membranes with low inorganic material retention and high organic material removal may create high-quality water.

A study conducted by Deepa et al. investigated the impact of diverse shapes of alumina NPs on the integrated polysulfone membrane's performance for the extraction of lignin from wood-based biomass and salt rejection.[340] The membrane was synthesized utilizing alumina NPs of spindle, cubic, and spherical shapes. The PSf/A3 membrane, which had a cubic shape, exhibited a notable lignin rejection rate of 98.6%. The PSf/A3 membrane's inner pores alongside narrow channels exhibit a high degree of selectivity, effectively impeding the movement of lignin via the membrane and resulting in a high degree of lignin rejection. Another study by Liu et al. investigated the antibiofouling properties of TFC NF membranes grafted with biogenic silver NPs.[341] The process of synthesizing biogenic silver NPs (Bio-Ag^0-6) involved the utilization of *L. fermentum* LMG 8900. The hydrophilicity and water flux of TFC NF membranes were improved by the incorporation of biogenic AgNPs. The grafting of biogenic AgNPs resulted in superior membrane stability compared to chemical AgNPs. The biogenic silver NPs (AgNP) grafted onto the nanofiber (NF) membrane exhibit superior antibacterial efficacy.

Pervaporation. Pervaporation (PV) dates back to the 1910s, when Kober coined the word "pervaporation" from "permeation" and "evaporation" of selective water transfer through parchment or collodion.[342] Pervaporation is an effective method for separating liquid solutions comprising tiny molecules, such as water and organic solvents. The bulk of both academic and industry research on pervaporation processes has focused on solvent dehydration, which may break azeotropes (alcohol/water) based on the water affinity and size discrimination impact of a hydrophilic membrane rather than the inclusion of an entrainer. Pervaporation has been extensively explored in the last two decades for the separation of tiny quantities of volatile organic compounds (VOCs) from water. This aspect's main emphasis is the recovery of bioalcohol (e.g., ethanol, butanol) from aqueous solution utilizing hydrophobic pervaporation membranes. Despite significant challenges in membrane stability and selectivity, pervaporation has been used to separate organic/organic mixtures with similar physicochemical features (aromatic/aliphatic), which is a critical and energy-intensive process in the chemical industry. Pervaporation membrane materials' design strategy, manufacturing technique, physicochemical attributes, pore structures, separation performance, and transport mechanism are all important in effectively being used in water treatment. The membranes are divided into 4 categories based on the material used to design them: polymeric membrane, inorganic, 2-D membranes, and mix-matrix membranes.

Extensive research has been conducted on the integration of NMs into pervaporation (PV) membranes, while the exploration of incorporating biogenic NPs into PV membranes remains relatively scarce. The study conducted by Kamtsikakis et al. examined the potential of CNCs as a modifiable NM for pervaporation membranes that exhibit asymmetrical transport characteristics.[343] The present study reports on the development of compositionally graded membranes utilizing a hydrophobic matrix and CNCs. The CNCs underwent surface alteration with oleic acid to achieve hydrophobicity as an optional step. The direction-dependent transport of membranes is attributed to their asymmetric structure. The utilization of hydrophobized CNCs in membrane fabrication has been observed to result in enhanced ethanol permeability. Another study conducted by Prihatiningtyas et al. explored the utilization of CNC as organic nanofillers in cellulose triacetate membranes for the purpose of desalination through pervaporation.[344] The introduction of CNCs resulted in a transformation of the membrane structure from a spongelike configuration to a self-assembled structure. The results of the PV experiments indicate that the inclusion of 3% CNCs in a CTA membrane led to a significant improvement in water flux, increasing it by a factor of 3 from 2.16 to 5.76 kg m^{-2} h^{-1}. The optimization process involved a reduction in the height of the casting blade from 200 to 100 μm, resulting in a flux of 11.68 kg m^{-2} h^{-1} and maintaining a NaCl rejection rate of 99.9%.

Electrodialysis (ED). ED is part of membrane desalination technology. ED is similar to ion exchange but differs in utilizing cation- and anion-selective membranes to separate charged ions.[345] It passes the saline solution through a membrane setup with two chambers. The chambers are separated by the membrane, which is selective toward allowing ions but not the molecules. One chamber has an anode, another one has a cathode, and the electric current is applied to aid in the migration of ions from one electrode to the other. The migration of ions results in separation of salt ions from the solution by creating a concentration difference. The desalinated water is discharged from the system, and the ions are collected in the chamber. Regular automatic polarity reversal has introduced an improvement in the ED process. This helps in decreasing the fouling process.[346] Many industrial operations produce salty wastewater, which must be desalinated before reuse or disposal. To that end, the use of ED has been investigated for the following major types of industrial wastewater: produced water from oil and gas extraction, sewage from refineries and petrochemical industries, drainage wastewaters from coal mining, and wastewater from power plants. ED treatments for industrial wastewater may be categorized in the separation of heavy metal ions, regeneration of acid/base, and desalination. Researchers globally are diligently endeavoring to enhance the efficacy of ED membranes' efficacy by incorporating NPs into the mix. Despite the potential benefits, integrating biobased NMs into ED membranes has yet to be fully realized, as indicated by the limited number of research articles currently available on this subject.

■ CONCLUSION

This review highlights the significant role bio-NMs can play in effectively resolving the immediate challenges associated with water purification. The potential of bio-NMs is extensive and varied, stemming from a wide range of biomass sources, including agricultural waste and microorganisms such as algae and fungi, as well as various NP synthesis processes. The paper extensively examines the diverse range of NMs, including cellulose and metal-based variants, while emphasizing their distinct characteristics and practical uses. The uses of these materials showcase their flexibility, as they are used in several areas such as nanoscale filtration and pollutant adsorption for wastewater treatment as well as their potential contribution to desalination technology. The many instances documented in the literature effectively highlight the increasing attention and progress within this particular sector. In conclusion, it is apparent that bio-NMs not only provide a viable and environmentally friendly substitute for conventional approaches but also have the potential to significantly transform water treatment and desalination procedures.

■ FUTURE DIRECTIONS AND PERSPECTIVES

The investigation of bio-NMs in the field of water purification signifies the beginning of a new age of sustainable approaches, leveraging abundant resources provided by nature. This study provides a comprehensive analysis of the recent advancements in the synthesis of NMs using environmentally sustainable approaches, with a particular focus on the use of biomass as a crucial precursor. The increasing threat posed by environmental toxins highlights the need to enhance and strengthen the current cleanup procedures. The use of bio-NMs has undeniable ecological advantages, providing a sustainable alternative to conventional approaches. The use of many sources, ranging from algae to agricultural waste, to produce these materials highlights the rich and diversified resources available in nature for the sake of environmental restoration.

However, despite the seeming promise of bio-NMs, there are still some persistent difficulties that need to be addressed. The need for transitioning laboratory-scale findings to industrial applications, particularly with regard to scalability, remains of utmost importance. Further investigation is required to examine the endurance and robustness of bio-NMs, particularly in comparison to their synthetic equivalents. It is crucial to acknowledge that while a technique may include environmental friendliness, it should not lack effectiveness. Further investigation is required in order to comprehend the intricate relationship between sustainability and performance.

The economic feasibility of implementing large-scale bio-NM deployment is a subject of ongoing discussion and analysis. Although the initial investments required may be large, the possible long-term advantages, such as decreased expenses for environmental remediation and potential regulatory incentives, have the ability to shift the balance in favor of a positive economic projection. In the past few years, there has been a notable rise in the development of novel methodologies. These methodologies include the use of various NMs, the integration of NMs with sophisticated substrates, and the application of botanical extracts for the synthesis of new NMs. Several other sources, including microalgae, chitosan, and bacteria, have shown significant promise in advancing the development of bio-NPs.

Although there have been several studies conducted on the use of bio-NMs for adsorption applications, there is a noticeable lack of research exploring their potential application in desalination technologies. This discrepancy highlights a relevant research opportunity. As the worldwide need to mitigate the freshwater shortage becomes more pressing, the incorporation of environmentally friendly NMs into desalination methods is a viable and economically viable approach. The process of transitioning from controlled conditions to practical, real-world applications has significant importance. The full potential of bio-NMs can be fully understood and harnessed only via rigorous testing in many uncontrolled environments. This underscores the need to conduct extensive studies that thoroughly assess both the efficacy of bio-NMs and their long-term ecological consequences.

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