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Recent Advances of Nanotechnology in Mitigating Emerging Pollutants in Water and Wastewater: Status, Challenges, and Opportunities

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Abstract Availability of clean and safe freshwater has become a looming global concern. The accelerated demography, industrialization, and climate changes contaminate the meager freshwater reserves. Pollution of water bodies is significantly detrimental to health, ecology, economy, and society. The rising number of malnutrition cases, stunted growth, hepatitis, gastroenteritis, skin ailments, cholera, respiratory disorders, liver malfunction, eye infections, and mortality have been attributed to exposure to compromised water. Thus, optimized, durable, and inexpensive wastewater treatment and remediation processes are necessary. Current conventional treatment strategies suffer from several drawbacks, which may be mitigated through nanotechnological intercession, promising sustainability. Nanomaterials include nanosorbents, carbon nanotubes, nanocomposites, nanofibers, graphene, nanodendrimers, nanomembranes, and nanocatalysts. They have unique properties that make attractive alternatives for wastewater remediation, purification, and contamination detection through pollutant-specific nanosensors and detectors. This review discusses water pollution, its impacts, conventional treatment strategies, nanotechnological contributions, venture possibilities, and associated commercial opportunities.

Keywords Nanocomposites · Nanoadsorbents · Nanomembranes · Photocatalytic nanomaterials · Bioremediation

1 Introduction

Access to unpolluted water sources is an escalating global environmental challenge. It is further compounded by the exponential growth of population, industrialization, climate changes, and, though trivial, a perceptible general indifference towards this imminent calamity. Mounting municipal and industrial wastes, discharge from agricultural residues fraught with fertilizers, pesticides, and other chemicals, and

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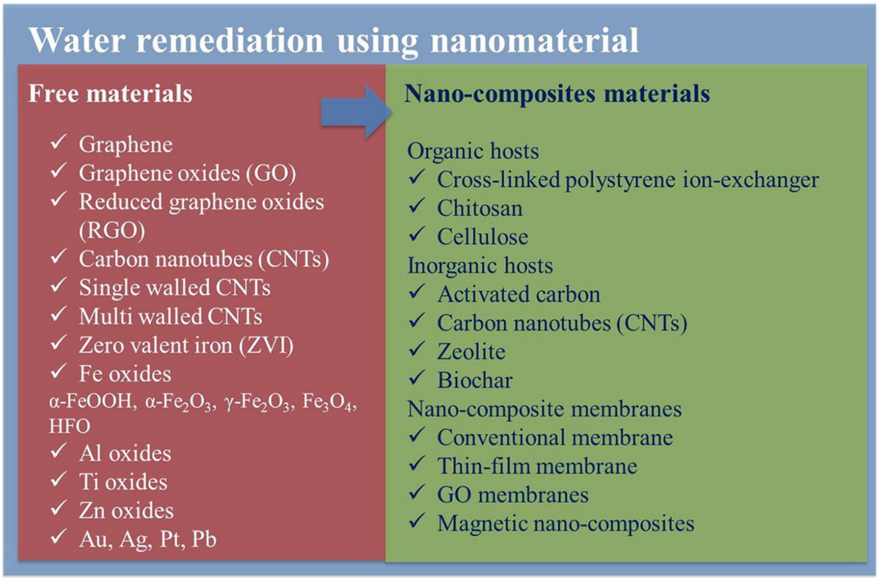
seawater intrusion are slowly but surely overwhelming the limited clean and safe water reserves. Excessive amounts of pollutants in water render it unsuitable for domestic and other uses (Maulin, 2017). Currently, various agrochemicals and industrial products that are structurally racemic are in use that are contaminating the water reserves (Basheer, 2018a). Pesticides carcinogenicity and tissue degradation are extremely hazardous as groundwater contaminants (I. Ali & Jain, 1998). The control and remediation of such pesticide stereomers have been researched using kinetic models (Basheer & Ali, 2018). The use of various nanosorbents to remove drug and pharmaceutical residues from contaminated water has been discussed (Basheer, 2018b). Several inorganic pollutants comprise metal ions that exhibit carcinogenicity at high concentrations and toxicity to biodiversity.

The various techniques of metal ion speciation and their applications have been reviewed (I. Ali et al., 2005; I. Ali & Aboul-Enein, 2002). The removal of various metal ion species through modified graphene (I. Ali, et al., 2018a, 2018b, 2018c; I. Ali et al., 2019b) and metal nanodots (I. Ali et al., 2018a, 2018b, 2018c) have been reported by various authors. These pollutants contaminate rivers, lakes, reservoirs, streams, seas, aquifers, and oceans, which degrade the water quality and become toxic to humans or the environment contributed by excessive salt content, silt, heavy metals, algae, and pathogenic microbes. The world is no stranger to population decimation through epidemics, and the brotherhood between disease and waterborne microbes is well known. Pollution of water resources has significant health, ecological, economic, and social impacts. The necessity for environmentally safe water supply is especially imperative for developing nations in rural regions/urban areas that experience inadequate facilities and technologies for the purification and remediation of wastewater. According to the World Health Organization report (2014), over 700 million people worldwide have limited access to freshwater resources. Hence, sustainable water and wastewater remediation and management strategies are paramount (World Health Organization, 2014). Various nanomaterials employed for wastewater remediation are shown in Fig. 1.

Wastewater remediation is the treatment, reversal, and reclamation of water bodies through technologies and management systems. There are currently various traditional methods for treating water based on its source and use, such as domestic, drinking water, agricultural, or industrial. Evaporation, biochemical processes, filtration systems, chemical disinfection, and decontamination treatments are commonly used. Literature review studies reveal no ideal method for efficient remediation of complete pollutants from wastewater. High operating costs, selective decontamination, decreasing efficiency of the treatment plants, limited flow-through capacities are some of the limitations of conventional treatment techniques (Ashby

Fig. 1 Different nanomaterials used for wastewater remediation, (Copyright© Elsevier 2016. All rights reserved reprinted with permission) (Zhang et al., 2016)



et al., 2009; Kunduru et al., 2017). These drawbacks call for innovative, improved, and more sustainable technologies for integrated wastewater treatment and management. Nanotechnology and nanomaterials have promised engineering and technology such as electronics, medicine, and commercial products. Nanomaterials with prescribed properties such as aspect ratio, sieve diameter, tunable hydrophobicity, organophilic, antimicrobial property, and reactivity can require selectivity, sensitivity, adsorptivity, and catalysis for effective treatment of wastewater.

Nanotechnology-based processes promise efficiency, multi-functionality, durability, and high performance, albeit at a higher cost, which may be further optimized or offset with proper management. Various reports and reviews are available on the role of nanotechnology in water treatment (Gehrke et al., 2015; Patanjali et al., 2019), focusing on the treatments by classifying the various nanomaterial types. The current review classifies the different mechanisms used to treat contaminated water with nanomaterials. This review highlights water pollution, including water resources and contamination, conventional treatment methods, current nanotechnological interventions, venture possibilities, and commercial opportunities.

2 Water Pollution and Its Public Health Impact

Water, the universal solvent and source of all life forms on earth, is predominantly vulnerable to pollution. The discharge of pollutants in liquid or solid particles into water bodies changes water quality (Amin et al., 2014), causing it to become contaminated or polluted, thereby rendering it unsafe. Water pollution is highly empirical to public health, especially in the most hazardous zones, which impedes human health and safety and animals and plants. This low quality of water for domestic or agricultural purposes depreciates the health quality of inhabitants in the regions who depend on such water sources (Fawell & Nieuwenhuijsen, 2003; Owa, 2014). Water pollution may be caused by human activities that cause changes in the chemical (pH, chlorides, metals, alkalinity, organic and nutrient), physical (odor, color, turbidity, temperature, solids), and biological (algae, protozoa, worms, bacteria, virus) characteristics of the water, making it toxic for living organisms (Gambhir et al., 2012; Khatri & Tyagi, 2015; Khatun, 2017). Water pollution alters water's chemical, physical and biological nature that causes detrimental consequences on the living organism (S. Sharma & Bhattacharya, 2017). Excessive amounts of hazards or pollutants in water render it unsuitable for domestic and other uses. These pollutants contaminate rivers, lakes, reservoirs, streams, seas, aquifers, and oceans, which degrade the water quality and become toxic to humans or the environment, as shown in Fig. 2.

Any non-contagious public health outbreaks are due to environmental contamination caused by daily human activities. The repercussions of water pollution rise immediately or with time. According to the World Health Organization (2014), developing countries contribute to about 14,000 mortality cases attributed to exposure to poor quality water for domestic purposes (Owa, 2014; WHO, 2013). The consumption of human and animal feces contaminated drinking water or food causes diarrhea and other diseases. Thus it can be contagious when proper hygiene is not practiced and could promote malnutrition, stunted growth, and deaths in children below five years (Q. Wang & Yang, 2016).

Cyprian En (2011) asserted that certain groups (newborn babies, younger children, elderly, and individuals with medical transplants) are more vulnerable when exposed to contaminated water. Further, most deaths are not reported up-to-date in medical records due to the limited availability of facilities in rural communities where such cases are rampant (Alens, 2014; Cyprian En, 2011). The release of sewage into water bodies contributes to the poisoning of aquatic lives. The consumption of contaminated fish also poses a severe health threat, such as hepatitis, gastroenteritis, skin ailments, cholera, respiratory disorders, liver malfunction, and eye infections (Alens, 2014; World Health Organization., 2014).

In developing countries, daily human activities like bathing, swimming, cooking, washing, and drinking from contaminated streams and ponds expose and increase the susceptibility to health hazards, simply because it might be the only water source while waiting for rainy seasons for freshwater harvesting. Exposure to algae-infested water bodies either by consumption or direct contact leads to dreadful diseases like hepatitis B and liver damage (Vidal et al., 2017). Another water pollutant that poses a severe threat to both human and aquatic health is pesticides

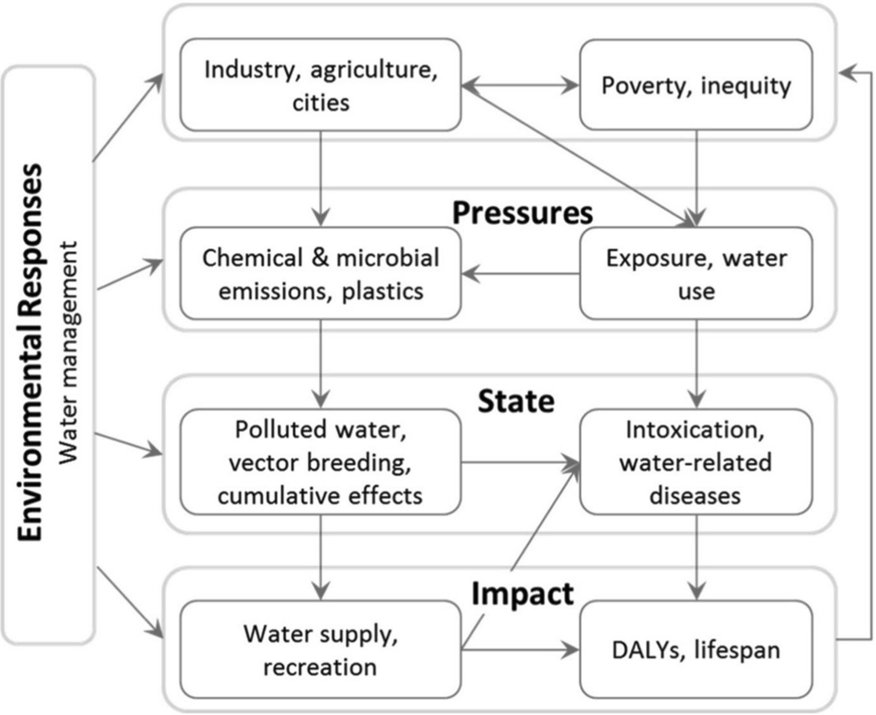


Fig. 2 Various drivers for water pollution and the impact on public health (Copyright© Elsevier 2019. All rights reserved reprinted with permission) (Boelee et al., 2019)

and fertilizers, such as DDT and nitrates on the farmland (N. Sharma & Singhvi, 2017). These poisonous compounds get into the water bodies through wash-off from the agricultural land where such compounds have been applied. Such compounds risk people's lives, causing children's congenital disabilities, cancer, thyroid, and health disorders (Roberts & Karr, 2012). Nitrates can affect underground and surface water, commonly seen in rural communities.

Vulnerability to human health can be attributed to diverse factors such as poverty, environmental issues, and limited access to basic health requirements (Lahsen et al., 2010). Therefore, the pollution of water bodies has substantial health, ecological, economic, and social impacts. Such health issues can be managed appropriately if effective mechanisms are in place. Thus crucial attention is necessary to improve water quality for domestic and other purposes.

Water pollution may be caused due to natural or anthropogenic activities (Kurwadkar, 2017). They can be broadly classified by order of contribution as industrial effluents (Jurado et al., 2012; Ntengwe, 2005; Rozman et al., 2017; N. Sharma & Singhvi, 2017; Q. Wang & Yang, 2016), municipal or domestic waste (Badila et al., 2018; Drinan & Spellman, 2012; Malinauskaite et al., 2017; Pandey et al., 2014; Stewart, 2013; Wen et al., 2017), agriculture waste (Cai et al., 2018; Cassou et al., 2018; Melo et al., 2012; Obi et al., 2016; H. Xie & Ringler, 2017; Y. Y. Zhao & Pei, 2012), biological waste (Aniyikaiye et al., 2019; Pandey et al., 2014), radioactive waste (Skipperud & Salbu, 2018) and oil spills (IPIECA-IOGP, 2015; Jernelöv, 2010; Saadoun, 2015) that contaminate the water bodies to a broader extent. Global statistics show that industrial waste constitutes 97% of water pollution (Stewart, 2013). The EPA encourages waste management practice by eliminating chemical waste formation through reduction processes at the source itself, followed by recycling, the combusting process for energy recovery, remediation, and disposal into the environment. The European waste framework directive (Directive, 2008) is depicted in Fig. 3. Various water resources contaminated by anthropogenic activities are illustrated in Fig. 4.

2.1 Localized and Delocalized Water Pollution

Localized pollutants originate from a point or discrete source. They include discharges from industrial discharge, municipal sewage remediation

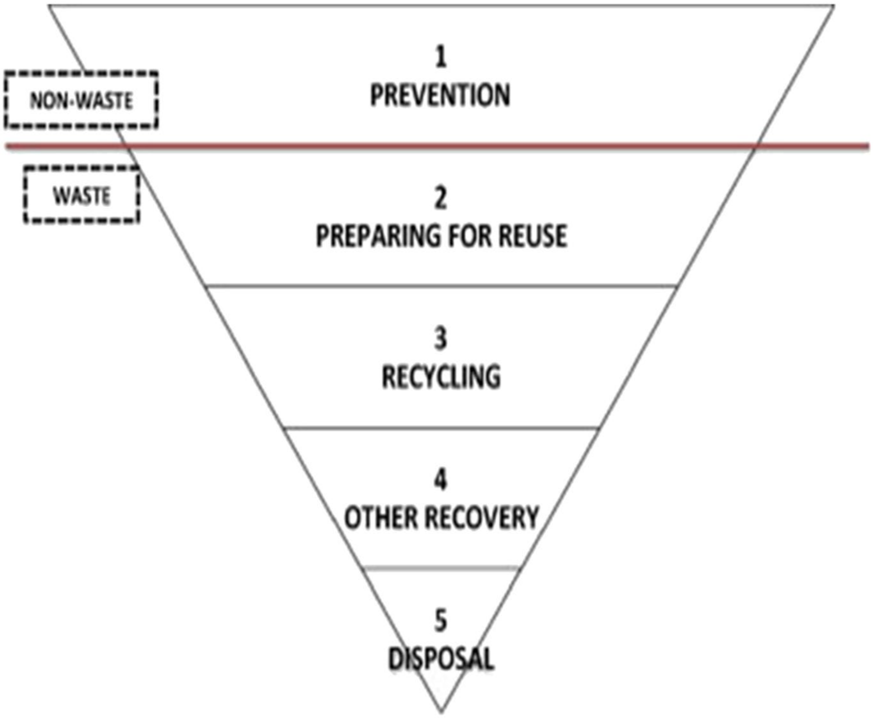


Fig. 3 Hierarchy scheme for waste management (Directive, 2008). (Copyright© Elsevier, 2015. All rights reserved reprinted with permission) (Gharfalkar et al., 2015)

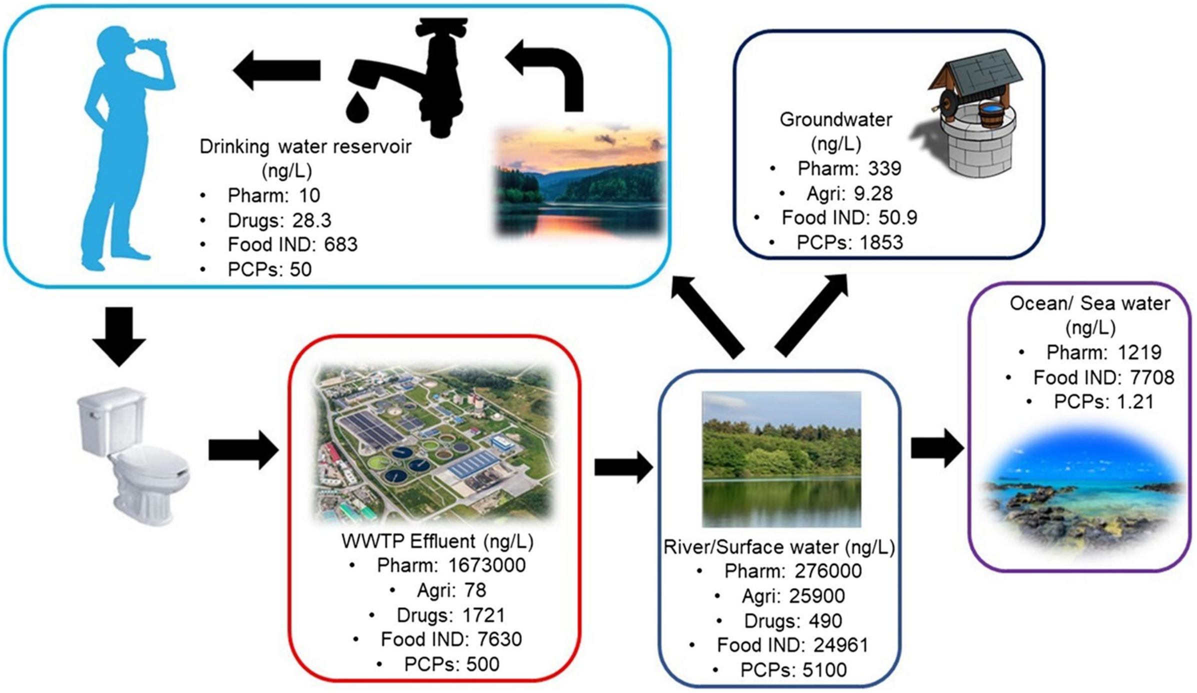


Fig. 4 Water sources contaminated by anthropogenic pollutants. (Copyright© Elsevier, 2019. All rights reserved reprinted with permission) (Lopez-Pacheco et al., 2019)

plants, spills from sewage stormwater, resource extraction, and landfill disposal sites. The U.S. Clean Water Act (CWA) defined this water pollution category for regulatory enforcement purposes and reformed it in 1987 to encompass municipal storm sewer systems and industrial stormwater sourced from construction areas. However, these pollutants can be managed and monitored through a controlled system (Owa, 2014; Solomon et al., 2002).

The contaminants in delocalized water pollution originate from poorly defined sources or groups of human activities with no specific entry point into the water bodies. These occur over broad geographical areas and are often difficult to trace their direct discharge source. Examples include agricultural runoff (fertilizers, pesticides, and pathogens), atmospheric deposition, urban and stormwater runoff, and persistence of organic contaminants mercury and polychlorinated biphenyls (PCBs) due to wet and dry deposition (Nemcic-Jurec & Jazbec, 2017; Solomon et al., 2002).

Transboundary water pollutants like nuclear waste affect the environment and health hundreds of miles away from the source of origin and cross-country. The continuous discharge of contaminants into water bodies through the centuries has modified the water flow pattern and has altered transboundary riverine system stopography. Thus seriously affecting aquatic ecosystems and the healthy development of a sustainable economy and society (S. Yu & Lu, 2018). Table 1 abridges dangerous pollutants from various sources (Mongillo, 2008).

Water plays a prominent role in irrigation and manufacturing industries for domestic purposes. However, human activities such as industrial operations, fertilizers and pesticides, oil spills, and leakages from landfills cause water contamination (F. Fu & Wang, 2011; Hladik et al., 2005).

Wastewater remediation is necessary to minimize the adverse effects caused by the wastewater release into water bodies and its detrimental effect on public health. The conventional procedures for eliminating contaminants are insufficient to meet present regulatory limits due to expensive treatment technologies. Hence, economic and green technologies are always in high demand.

The conventional practices include physical remediation methods (Alter, 2012; F. Fu & Wang, 2011; Hargreaves et al., 2018; Hoslett et al., 2018; Samer, 2015; X. H. Zhang, 2011), biological remediation (Azubuike et al., 2016; Lampis et al., 2015; Lim et al., 2014; Mahimairaja et al., 2005; Nzila et al., 2016; Yang et al., 2012) and chemical remediation methods (Acharya et al., 2018; Akpor, 2014; Ariffin et al., 2017; R. Das et al., 2014; Ersahin et al., 2012; F. Fu & Wang, 2011; Hegazi, 2013; Malik et al., 2017; Saha & Sinha, 2018). Also, microorganisms (algae, bacteria, fungi, and yeast) can be used to eliminate or recover toxic metals derived from industrial contaminants (Igiri et al., 2018; Migahed et al., 2017**).** A schematic flow of conventional wastewater treatment is depicted in Fig. 5.

However, most conventional treatment strategies suffer drawbacks related to operational methods, processing efficiency, economic boom, and energy

Table 1 Localized and delocalized sources of pollutants

		Bacteria	Nutrients	Dissolved Ammonia	Solids	Acids and Toxics
Localized sources	Municipal waste remediation plants	√	√	√		√
	Industrial services				√	√
	Sewer outflows	√	√	√		√
Delocalized Sources	Agricultural runoff	√	√		√	√
	Urban overflow	√	√		√	√
	Construction overflow		√			√
	Mining overflow				√	√
	Septic systems	√	√		√	√
	Landfill spillage					√
	Forestry overflow		√			√

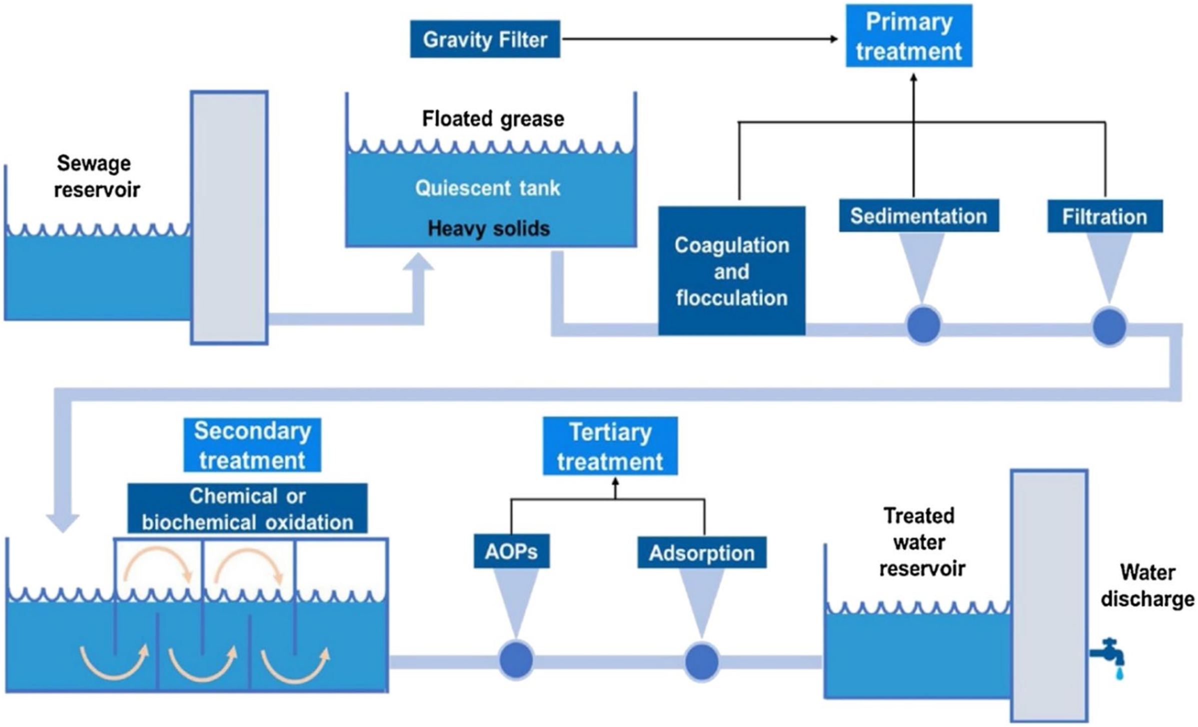


Fig. 5 Conventional wastewater treatment flow chart. (Copyright© Elsevier, 2019. All rights reserved reprinted with permission) (Zhao et al., 2019a)

requirements, thus reducing their wide-scale and long-term practical applicability.

Nanomaterials to extract pollutants have gained immense attention from the research groups (Werkneh and Rene, 2019). Some of the advantages and limitations of conventional methods are highlighted in Table 2 (Ariffin et al., 2017; R. Das et al., 2014).

3 Nanotechnology in Wastewater Treatment

Providing hygienic and reasonably affordable potable water is one of the chief global challenges this century faces necessitating sufficient planning and management stratagems (Kunduru et al., 2017). Besides, inaccessibility to fresh water in many developing nations affects millions of families worldwide and is an issue that requires resolution sooner than later (Qu, Alvarez, et al., 2013; Qu, Brame, et al., 2013; Thines et al., 2017). The rapid population growth, extensive industrial development, climate change or extended droughts, stringent regulations, and contentious water demands have contributed to the deteriorating physicochemical and biological characteristics of the existing water resources making it an international concern (Lu et al., 2016; X. Xu et al., 2012; Zeng et al., 2011). The use of chemicals and metals in various industries produces bulk quantities of waste containing high concentrations of hazardous heavy metals and liquid waste (Coetser et al., 2007). Additionally, groundwater is frequently polluted by effluent spillage, irregular agricultural methods, unscrupulous domestic waste discarding approaches, and leakage of underground reservoir tanks, leading to environmental hazards, public health threats, and economic instability (Kemper, 2004). Due to less efficient water distribution and sanitation practices, large squalors are released into the nearby water bodies from the industrial sectors. The increased concentrations of toxic pollutants and other complex compounds in the water bodies have a devastating effect on public health (X. Xu et al., 2012; Yue et al., 2015). Consequently, it is imperative to eliminate these contaminants from effluents before releasing the processed

Table 2 Advantages and limitations of traditional water treatment methods

Process	Advantages	Limitations
Adsorption	• Easy operation • Simple and flexible design	• Decrease in efficiency over time • Requires frequent desorption/cleaning
Biological treatment	• Can be carried out in situ • No toxic end products • Natural process	• Difficult to control • Microorganisms are sensitive to environmental factors • Not easily commercialized • Not cost-efficient • Removes only a few metals • Time-consuming
Carbon filter	• Low cost • No foreign chemicals added • Removes organic chemicals and disinfectants	• Removal of metals, nitrates, fluorides, metals, sodium is not possible • Prone to clogging with undissolved solids • Requires frequent changing of filters • Susceptible to mold
Chemical treatment	• Rapid process • Easy to implement	• Environmentally hazardous end products or intermediates • Excess reagents are required • High energy requirement • Not highly selective
Coagulation and flocculation	• Economical and feasible • Limited investment	• Complicated and less productive • High sludge production • Demands alkaline additives
Distillation	• Flexibility to handle a wide range of feed flow rates • Applicable to a wide range of feed concentrations • Separation of homogenous mixtures	• High energy and water requirement • Most contaminants remain behind • Contaminants with a boiling point greater than 100 °C are tedious for removal
Membrane filtration	• Good removal of heavy metals • Reliable	• Expensive • High energy consumption • Limited lifetime • Prone to membrane fouling Requires pretreatment
Microfiltration/ Ultrafiltration	• No foreign chemicals used • Not expensive • Suitable for a variety of particulate separations	• Does not remove dissolved inorganics and volatile organics • Less sensitive to pathogens, viruses • High energy requirement • Susceptible to particulate clogging
Reverse osmosis	• No foreign chemicals added • Removes many dissolved substances efficiently	• It also removes essential minerals making them unhealthy • Difficulty in removing volatile organic compounds and pharmaceuticals • Exposed to membrane fouling • The treated water is acidic
Ultraviolet treatment	• Eliminates bacteria, viruses, and coliforms • No sludge production	• Expensive • Deprived of capacity by water turbidity • Ineffective for heavy metals

water into the environment/water supply for household consumption.

The current nanotechnological developments in water treatment involve using nano-adsorbents, nanomembranes, nanocatalysts, and nanobioremediation. Although various technologies are utilized to treat wastewater ranging from precipitation and flocculation to electrochemical methods and biodegradation, adsorption technology is one of the most economical, productive, and eco-friendly processes. The use of nanomaterials in the preparation of various adsorbents in recent years encompasses metal and metal oxide particles, carbon nanotubes, dendrimers, zeolites, and graphene nano-adsorbents. Nanofiltration and its combination with other methods are widely used for water desalination and purification. Diverse nanomembranes highlighted in recent studies include nanomaterials based on carbon nanotubes, inorganic polymers, nanometals, nanofibers, nanocomposites, and nano-ceramic membranes.

Furthermore, the applicability of photocatalytic nanomaterials has also been widely studied. Recent advances include titanium oxide nanoparticles, titanium oxide-based polymeric composites, and doped titania nanoparticles with other metals such as boron, manganese, cobalt and iron, and hybrid palladium ferric oxide nanocatalysts. Last but not least, nanobioremediation is currently viewed as a sustainable technology where microbial cultures, extracts, and biomolecules are employed to produce bio-nanomaterials for water remediation and treatment.

The various nanotechnologies have reduced pesticide levels over 20 times compared to conventional procedures to as low as 0.5 ppb (Nagar & Pradeep, 2020). A composite membrane prepared from carbon nanofiber on ceramic substrates exhibited a pore size of ~ 30 nm and an extremely high salt rejection capability nearing 99% and 20 times higher water flux than conventional polymeric membranes (W. Chen et al., 2018). Kevlar aramid nanofibers and their composites have been shown to reject over 96% of Rhodamine B (Li et al., 2019) and a desalination efficiency of over 99.5% for sodium sulfate (Y. Zhao, Chen, et al., 2019; Zhao, Qiu, et al., 2019). Metal–organic nanostructures have demonstrated 72% permeability to pure water (Zirehpour et al., 2016).

3.1 Nanotechnology in Water Treatment and Its Significance

Nanotechnology is a revolutionary science that can overcome the current water pollution crisis challenges through innovative techniques (Shukla et al., 2018). The unique properties of nanomaterial render it an attractive process for water treatment. They have a large surface area to volume ratio with their size and shape-dependent than the bulk particles. The higher the surface area to volume ratio, the more robust, more stable, and durable the nanomaterial. They have a high affinity toward a given compound when functionalized with other chemical groups. They can develop highly efficient water treatment tools because of its small size, large surface area to volume ratio, physical, chemical, redox, and catalytic properties(F. Lu & Astruc, 2018). Nanoparticles (NPs) can be tethered onto a stable solid matrix such as activated carbon or zeolites, natural clays, and crop residues to enhance the remediation efficiency (Bhattacharya et al., 2013). It can also percolate into the groundwater and remain suspended for sufficiently long durations (M. Wang et al., 2016).

Natural or engineered nanomaterials can be broadly classified into 0-D NPs (e.g., atomic clusters), one dimension (e.g., nanorod, nanowires), 1-D (e.g., surface films, thin films, fibers, graphene, and carbon nanotubes), or 3-D (nanophase materials like dendrimers). NPs can exist as single, fused agglomerates or aggregates in different shapes as tubular, spherical, and irregular forms (Tiwari et al., 2012). The types of nanomaterials available are metal-based NPs (gold NPs, silver NPs, quantum dots, titanium dioxide), carbon-based nanomaterial (nanotubes and fullerenes), dendrimers (nanopolymers), nanocomposites (nanoclay), nanofibers (NFs), graphene, and nanowires (I. Ali et al., 2020; I. Ali et al., 2018a, 2018b, 2018c; I. Ali et al., 2019b; Tlili & Alkanhal, 2019); Lu et al., 2016; Tiwari et al., 2012).

NPs and nanomaterials unique features are anticipated to help solve the water treatment challenges involving eliminating impurities such as pathogens, pharmaceuticals, perchlorate, pesticides, toxic heavy metals, and other persistent and hazardous chemicals (I. Ali et al., 2021; Ali, Babkin, et al., 2021; Ali, Zakharchenko, et al., 2021; Kunduru et al., 2017; Zekić et al., 2018). They may also be used in the remediation of toxic metal ions by membrane concentrates from wastewater (Bart Van Der Bruggen et al., 2003), development of chlorine-free biocides (D. Kim et al., 2009), and desalination of brackish water (Cong, 2018). Nanomaterials can kill pathogenic microorganisms without forming hazardous byproducts (Qu, Alvarez, et al., 2013; Qu, Brame, et al., 2013). As per (Adhena Ayaliew Werkneh & Rene, 2019), some of the ideal features for nanomaterial-based disinfectants are:

i. They must be non-corrosive and easy to store.

ii. They should not form harmful disinfectant by-products.
iii. They should have low environmental toxicity.
iv. They must address a broad spectrum of microorganisms.
v. The disinfection process should occur within a short time.
vi. They must be easy to operate with low energy consumption process.
vii. The sludge should be safe for final disposal after treatment.

Some such nanomaterials include, but are not limited to, nanosilver (Rai et al., 2009), chitosan NPs, which destruct the cell membrane through direct contact (Higazy et al., 2010), zinc oxide NPs (Qu, Alvarez, et al., 2013; Qu, Brame, et al., 2013), and NPs of TiO_2 which generate reactive oxidative species (Hebeish et al., 2013). Nanomaterials potential applications are not limited to remediation and purification of water through partial or complete removal of pollutants and contamination detection through pollutant-specific nanosensors and detectors (Kunduru et al., 2017).

A recent innovation by (Boatemaa et al., 2019) shows that nano bioconjugated gold may be interested in detecting typhoid, causing *Salmonella* strains and profound potential use in water quality assessment and biomedicine as an alternative antibiotic. Figure 6 represents a schematic representation of various biobased nanomaterials employed for wastewater remediation.

3.2 Nanosorbent Materials for Water treatment

Nanosorbents are used as separation media to remove inorganic, organic, metals, and ionic pollutants from contaminated water. Nanosorbents can be metal oxide-based, carbon nanotubes based, dendrimer based, zeolites based, metal NPs based, or self-assembled monolayers on mesoporous supports (SAMMS), which blends mesoporous ceramics with self-assembled monolayer chemistry, creating sorbents that have the potential for removing metals and radionuclides from water (Tuccillo et al., 2012). These materials have a specific affinity to different contaminants, large surface area, fast kinetics, high adsorption efficiency, and high reactivity (Tijing et al., 2019).

3.2.1 Metal Oxide Nano-adsorbents

Metal oxide-based nanomaterials have unique advantages for eliminating heavy metals due to their high reactivity, good adsorption, photolytic and catalytic properties in the presence of heat or light source, and their affinity towards pollutants can be improved by using various functionalized groups (Klaine et al., 2008). For instance, the effectiveness of magnesium oxide NPs and magnesium NPs has been experimented with as specific bactericidal against *Escherichia coli, Bacillus megaterium,* and *Bacillus subtitles* (Raghunath & Perumal, 2017).

Zinc oxide NPs inherit the ability to remove arsenic from water; iron oxide (I. Ali et al., 2018a, 2018b, 2018c) and titanium dioxide (I. Ali et al., 2018a, 2018b, 2018c) are suitable sorbents for metal contaminants, while magnetic NPs are reported to be more beneficial than magnetic beads (Elbana & Yousry, 2018). The most-reported oxides are titanium dioxide, zinc oxide, iron oxide, cerium oxide (Baranik et al., 2018), magnesium oxide, and aluminum oxide (Mayo et al., 2007). Copper oxide NPs and copper oxide integrated mesoporous alumina are beneficial for As(III) and As(V) adsorption (Martinson & Reddy, 2009)**.** In some developing nations, iron oxide-coated silica has also been investigated as promising management of arsenic. Olyaie et al. (2012) have proposed an innovative and cost-effective approach to removing arsenic contamination from water by calcium peroxide NPs. According to the report, NPs effectively removed arsenic content at the natural water pH range between 6.5 and 8.5 (Olyaie et al., 2012). However, the efficacy of calcium oxide NPs decreased with increasing pH and arsenic concentration.

3.2.2 Carbon Nanotubes (CNTs) Nano-adsorbents

Carbon-based adsorbents are highly versatile and are heavily used to eliminate various pollutants, including heavy metals. Carbon-based nanomaterials come in different shapes such as nanowires, nanotubes, fullerenes, and sizes such as hollow spheres, tubes, ellipsoids, or hexagonal structures (Zaytseva & Neumann, 2016). Carbon nanotubes have widely been studied for their unique property and application as nano sorbents (Z. Wang et al., 2018)**.** It has the potential to remove heavy metal ions from wastewater and act as sorbents due to its high surface area and selectivity

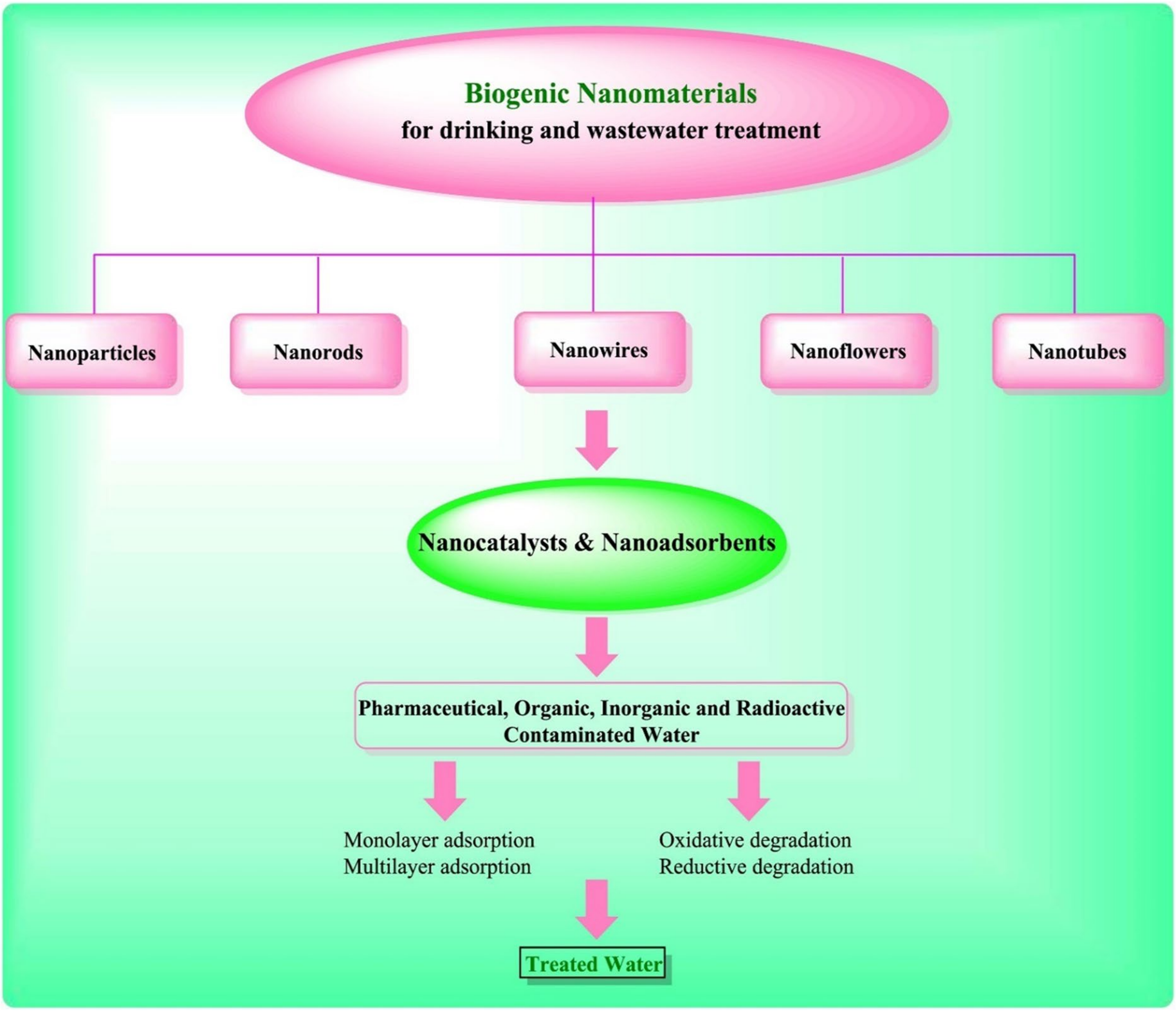


Fig. 6 Various biogenous nanomaterials for wastewater remediation. (Copyright© Elsevier, 2021. All rights reserved reprinted with permission) (Nasrollahzadeh et al., 2021)

for organic solutes, excellent thermal and electrical conductivity, high stability, tunable reactivity, composed entirely of carbon, and are potent antioxidants (Ali, Rehman, et al., 2019; X. Wang, Lin, et al., 2012; Wang, Guo, et al., 2012).

Reports are available on the use of CNTs as a sorbent to remove heavy metals such as nickel (Farghali et al., 2017), lead (Kabbashi et al., 2009), chromium (Anastopoulos et al., 2017), copper (Li et al., 2010), and cadmium (Kuo & Lin, 2009). Carbon nanotubes are of two types: single-walled CNTs (SWCNTs) or multi-walled CNTs (MWCNTs). Multi-walled CNTs have been tested to absorb 2,4,6-trichlorophenol and Cu(II) contaminants in water (G.-C. Chen et al., 2009).

Pillay et al. (2009) investigated the adsorption capabilities of CNTs for the removal of parts per billion levels (ppb) of Cr (VI) by using functionalized and non-functionalized MWCNTs (Pillay et al., 2009). The non-functionalized MWCNTs showed the highest adsorption capability, 98% for 100 ppb Cr (VI) solution.

Farghali et al. (2017) investigated the adsorption of Pb(II) using acidified MWCNTs. They found that the oxygen functional groups on MWCNTs play a vital role in Pb(II) adsorption to form chemical complexes, which account for over 93% of all the Pb (II) adsorption capacity (Farghali et al., 2017). CNTs to remediate heavy metal by adsorption is more efficient than granular activated carbon since CNTs can adsorb organic contaminants like dichlorobenzene and PAHs (Peng et al., 2014; Y. Wang et al., 2019).

3.2.3 Dendrimeric Nano-adsorbents

Dendrimers are monodispersed, hyper-branched, well-defined macromolecules with controlled composition and 3-D architectures. A dendrimers structure depends on its physical and chemical properties with low and high molecular weight (dendrons and dendrimers, random hyper-branched polymers, dendrigraft polymers, and polymer brush) (Ghasemzadeh et al., 2014). These dendritic polymers are highly efficient in ultrafiltration processes to grab the toxic metal ions, heavy metal ions, radionuclides, inorganic anionic pollutants, and organisms from contaminated water. The benefit of such membranes is that the bound ions can be washed post-filtration, and the dendritic polymer can be recycled (Diallo et al., 2004; Lu et al., 2016).

Dendrimers can also be functionalized with other materials like SBA-15 mesoporous silica and silica gel to recover metal ions from contaminated solutions (Shahbazi et al., 2011). Cross-linked polystyrene-supported diethanolamine has demonstrated good adsorption potentials for Cu^{2+}, Ag^{+}, and Hg^{2+} ions (SUN et al., 2006). Various dendrimeric polymers are in powder, or porous granules form that is easy to handle (Bethi & Sonawane, 2018). They also adsorbed organic and inorganic pollutants, including textile dyes from wastewater (Paulino et al., 2006), phenolic compounds (Turco et al., 2018), ammonia (Zheng & Wang, 2009), and heavy metals (Gad, 2008).

3.2.4 Zeolite Nano-adsorbents

The use of zeolites and silver has been dated since the early 1980s for contaminated water treatment. Zeolites have very porous structures in which NPs such as silver ions can be embedded subsequently released from the matrix through cation exchange in solution (B. Dong et al., 2014)**.** They are an effective sorbent and an ion exchange media for metal ions removal from contaminated water. There are sufficient reports of the use of zeolites in removing Cr(III), Ni(II), Zn(II), Cu(II), and Cd(II) heavy metals from metal electroplating and acid mine wastewaters (Alvarez-Ayuso, 2003).

Jung et al. (2004) developed nano-zeolites in series batch reactors for wastewater treatment, while Behari et al. (2008) fabricated nano-zeolites through laser-induced fragmentation of zeolite microparticles that serve as a new possibility of using only zeolites as NPs (Behari et al., 2008; Jung et al., 2004). Petrik et al. (2012) highlight the innovative use of zeolites as an adsorbing platform in conjunction with silver NPs as a disinfectant in the Water Research Commission Report No KV 297/12 (Ilka Gehrke et al., 2015; Petrik et al., 2012).

3.2.5 Metal Nanoparticle (MNP) Adsorbents

Metal NPs include nanoparticles of silver, gold, copper, palladium, or other metals. Jain and Pradeep (2005) reported silver ions and silver compounds as antimicrobial agents for coliform found in wastewater (Jain & Pradeep, 2005). NPs of gold crusted with palladium are highly effective catalysts for removing trichloroethane (TCE) from groundwater and are nearly 2,200 times better than palladium alone (Behari et al., 2008).

Engineered NPs such as zero-valent metals (bimetallic particles, emulsified iron) have good absorption properties in remediating wastewater. They are synthesized by reducing ferric or ferrous salts with sodium borohydride. They have high surface reactivity, which can be controlled by varying the reductant and the reduction conditions. The reactivity mechanism for zero-valent metals is similar to that of corrosion. They remediate water by adsorbing contaminants such as nitrates, trichloroethene, and tetrachloroethene (Aulenta et al., 2009; Pradeep & Anshup, 2009).

3.2.6 Graphene Nano-adsorbents

Graphene-based nanomaterials possess unique features that enable them to interact and eliminate heavy metal ions from contaminated water. Nanostructured carbon and charcoal have been used as adsorbents for aromatic compounds (Nasir et al., 2018). Exfoliated graphite nano-platelets have been proposed to adsorption phenolic compounds (Ion et al., 2011).

Copper silicate hollow spheres and functionalized graphene-based nanomaterials have been successfully synthesized and used as sorbents of trace pollutants and toxins to decontaminate water (I. Ali, et al., 2018a, 2018b, 2018c; I. Ali et al., 2019b). Hou et al. (2018) researched smart RNA aptamers covalently immobilized on graphene oxide nanosheets to precisely recognize and adsorb trace peptitoxins (microcystin-LR) in drinking water. The developed RNA-graphene oxide nanolayers could resist nuclease degradation and organic matter. Reduced graphene oxide/ferric hydroxide composites have been successfully tested for effective arsenate removal from water (Hou et al., 2018; Vuong Hoan et al., 2016)**.** Oxidized graphene has also been reported to remove rare-earth metals and nuclear wastes (I. Ali, Babkin, et al., 2021; Ali et al., 2021; Ali, Zakharchenko, et al., 2021; I. Ali et al., 2021; Ali et al., 2021; Ali, Zakharchenko, et al., 2021). Some of the recent advances of nanomaterials in wastewater remediation are highlighted in Table 3.

3.3 Nanomembranes for Water Treatment

Nanomembranes serve as advanced filtration or separation techniques to eliminate organic pollutants in water to meet the EPA's standards (Street et al., 2014). Nanofiltration and nanofiltration, and reverse osmosis are widely used for water desalination. Varieties of nanomembranes include CNT membranes, inorganic polymeric membranes, nanometals, nanofiber membranes, nanocomposite, and nanoceramic membranes.

3.3.1 Membrane-Mediated Nanofiltration

Nanofiltration is an efficient membrane-based technique for eliminating impurities from water without producing any harmful byproducts. A semipermeable membrane removes low molecular weight solutes, particles, fluids, gases, hardness (calcium and magnesium ions), and natural organic matter from the contaminated water (Abdel-Fatah, 2018; Egea-Corbacho et al., 2019; A. W. Mohammad et al., 2015). Van der Bruggen et al., (2000) studied the removal of fungicides, pesticides, insecticides, herbicides, rodenticides, and pyridine and chlorinated pyridine compounds (B. Van der Bruggen et al., 2001).

Nanofiltration membranes can be developed from polyamides, cellulose acetates, polyvinyl alcohol, polysulfones, and metal oxides. The pollutants adsorbed onto the membrane can be completely reversible (physical attachment), irreversible (strong chemical bonds), or both (Fane et al., 2011). Polyamide nanofiltration membranes of 250 Da or less are useful for removing hardness from groundwater. The nanofiltration process is also frequently used to remove natural organic matter (NOM) from water. The NOM is a polydispersed mixture of particles in water originating from decomposed plant residues (B. Van der Bruggen et al., 2001).

A further review of nanofiltration use to remove biological contaminants, cations, organic pollutants, NOM, nitrates, and arsenic from groundwater and surface water has been carried out by (Van Der Bruggen, 2003). The elimination efficacy of 1,1-bis(4-chlorophenyl)-2,2,2-trichloroethane (DDT) from polluted water using polyvinylidene fluoride (PVDF) membrane was evaluated. The authors demonstrated that the DDT concentration decreased significantly with high cumulative adsorption, indicating that the DDT was efficiently adsorbed on the PVDF membrane (Pang et al., 2010).

3.3.2 Carbon Nanotube (CNT) Membranes

CNTs have a wide application potential and can function as a membrane and its use as an adsorbent, as was highlighted earlier. CNT-based nanostructured membranes may be used as a tool for the elimination of bacteria and viruses from contaminated water. This membrane type is structured like a hollow cylinder comprising radially aligned CNT walls with a controlled density, geometric shape, and dimensions for specific applications.

It has high thermal and mechanical stability, a large surface area to volume ratio, and enhanced reactivity, making it a good separation membrane (Khin et al., 2012). The presence of pores could be useful in desalination and demineralization. Srivastava et al. (2004) fabricated a reusable CNT-based filter that serves as a membrane to remove *S. aureus* and *E. coli* pathogens and poliovirus (Sabin strain) from unclean water, which can be cleaned by ultrasonication or autoclaving(A. Srivastava et al., 2004). Chatterjee et al. (2005) reported a novel nanocapillary array membrane with the potential of reducing fouling tendency and enhanced solute retention (Chatterjee et al., 2005).

It was nanofabricated with a nonporous polycarbonate membrane of 30 nm pore size separated by

Table 3 Recent studies on Nanomaterials used for wastewater remediation

Types of nanomaterials	Application of nanomaterials	References
Silver NPs	Sorption of Cu^{2+} and Zn^{2+} heavy metal ions in water, antibacterial property	(W. Liu et al., 2018)
Graphene oxide	Removal of heavy metals and organic contaminants	(De Marchi et al., 2018)
Zinc oxide NPs	Sorption of various elements such as Al, Cu, As, Ni, Co, Hg, and Cd in the media	(Yamindago et al., 2018)
TiO_2 NPs	Remediation of organic (formaldehyde) and inorganic compounds	(Nam et al., 2019)
Nanofiber substance	Removal of contaminants in eutrophicated water	(Kenry and Lim, 2017)
Peptide nanosized electrodes	Detection of heavy metal ions	(March et al., 2015)
Histidine and glutamine functionalized silver NPs	Detection of Hg^{2+} ions and heavy metals	(Buduru et al., 2017)
CNTs	Treatment of pharma and antibiotic based contaminants	(Gehrke et al., 2015)
Magnetic NPs	Removal of As^{3+}, Cu^{2+} metal ions and organic pollutants	(Li et al., 2017b)
Polymeric based nanosorbents	Remediation of aromatic and phenolic compounds, dyes, and heavy metal ions	(Shan et al., 2017)
Zeolites	Remediation of radionuclides Cs^+ (2000 mg/g), Sr^{2+}(226 mg/g) and heavy metal ions Ni^{2+}(140 mg/g), Cu^{2+}(160 mg/g)	(Shilina et al., 2017)
Chitosan hydrogel loaded with MWCNTs	Removal of Congo red dye (423 mg/g)	(Santhosh et al., 2016)
Nano optical sensors	Detection of pathogens	(Mocan et al., 2017)
Fe NPs	Degradation of chlorpyrifos pesticide	(Mocan et al., 2017)
Polymer amended cellulose	Remediation of volatile organic compounds	(Guerra et al., 2018)
Zinc oxide/Graphene composite	Removal of methylene blue (MB) dye (97%)	(HOSSEINI et al., 2016)
Fe-nanocomposite	Fluoride removal (97%)	(Rout et al., 2015)
TiO_2/Graphene composite	Decontamination of water	(Tayel et al., 2018)
Ozone assisted MWCNTs	Pharmaceutical wastes	(Yanyan et al., 2018)
Fe_3O_4/Humic acid (HA) magnetic nano adsorbents	Toxic dyes	(R. K. Gautam & Tiwari, 2020)
Bismuth oxychloride (BiOCl) naosorbents	Rhodamine B dye decomposition (85.3%)	(Wu et al., 2020)
Magnetic TiO_2/Fe_2O_3	Remediation of pulp/paper industry effluent	(Subramonian et al., 2017)
Graphene Oxide/Fe_3O_4	Removal of Pb^{2+} (99.7%) from synthetic contaminated water	(S. M. Mousavi et al., 2018a, 2018b, 2018c)
Polyaniline-Fe_3O_4- silver diethyldithiocarbamate	Treatment of As, Hg, and Pb from aqueous solution and exhibited more than 99% removal capacity	(Hashemi et al. 2019)
Fe_3O_4 NPs	Removal of Ni^{2+} (93.8%) from wastewater	(Mousavi et al., 2018a)
Nanomaterial derived from Sugar beet processioning and clay brick solid waste	Removal of Cu (99%) and Cd (91%) from polluted water	(Lashen et al., 2022)
Graphene oxide coated with magnetic Fe oxide	Sorption of Erythrosine dye (149.25 mg/g) from aqueous media	(Mousavi et al., 2018b)
Nanomaterial derived from Moringa oleifera seed	Remediation chlorpyrifos (81%) from contaminated water	(Hamadeen et al., 2021)
Polyaniline-Fe_3O_4-Silver Diethyldithiocarbamate	Removal of Hg^{2+} (99%) in aqueous media	(Hashemi et al., 2020)
ZIF-8@Fe/Ni NPs	Removal of Malachite green (151.52 mg/g) from contaminated water	(T. Zhang et al., 2021)

Table 3 (continued)

Types of nanomaterials	Application of nanomaterials	References
Activated carbon@MgO@Fe_3O_4	Removal of As^{3+} (96.65%) from aqueous solution	(Esmaeili et al., 2021)
Cobalt-Tungstate ($CoWO_4$) nanomaterials	Degradation of Safranin T dye (74.57%) and other organic pollutants	(L. Xu et al., 2021)
Graphene coated Aluminum Fumarate Metal–organic framework (MOFs)	Efficient remediation of Congo red dye (178.5 mg/g) from contaminated water	(Azhdari et al., 2019)
Lanthanum oxide-spiked carbon nanomaterial	Phosphorous (48.8 mg P/g) remediation from diluted polluted water	(Xia et al., 2021)
3-dimensional cellulose nanofibril (CNF)	Treatment of Cu^{2+} (135.1 mg/g) from wastewater	(Hong et al., 2021)
Silica NPs derived from leaf biomass	Removal of Pb^{2+} (338.5 mg/g) and Cu^{2+} (179.4 mg/g) from synthetic polluted water	(Sachan et al., 2021)
FeS@Lignin-based carbon nanocomposite material	Remediation of tellurium (IV) (148.36 mg/g) from contaminated water	(Yao et al., 2021)
Zr-MnO_2@rGO nanocomposite	Removal of As^{5+} (99.3%) from water samples	(Yakout & Khan, 2021)
Ce spiked TiO_2 NPs	Remediation of organic pollutants such as MB (77%) and Rhodamine B dye (88%) from effluent water	(Keerthana et al., 2022)

poly dimethoxysiloxane-crossed microfluidic channels. Their tunable pore sizes suggest application as a functional material and building block in various water treatment processes.

A vertically aligned MWCNT membrane filter fabricated superoleophilicity and superhydrophobicity onto a stainless-steel net to separate immiscible liquids. The filter was shown to separate diesel and water layers and surfactant-stabilized emulsions. Moreover, phase separation of a high viscosity lubricating oil and water emulsions experimented successfully. Furthermore, it was concluded that the separation could be possible for various oleophilic and hydrophobic liquids, such as brewery wastewater effluent, which may contain a greater organic content than recommended COD and BOD (Khin et al., 2012).

3.3.3 *Inorganic Polymeric Nanomembranes and Nanometals*

These inorganic membranes are advantageous because they are easy to synthesize, relatively cheap, and functionalized for selective transfer of chemical species (Lee & Baik, 2010). In the harsh operational environments of an industrial process, inorganic membranes can offer their advantages. These positive attributes make them highly recommended for commercial applications since they have good mechanical strength, better resistance to chemical attack, and extraordinary tolerance to extreme pH and oxidation. Enhanced conversion ratio, milder operating conditions, better selectivity, and lower separation load are other striking characteristics that encourage the use of inorganic nanomembranes as chemical reactors (Labbez et al., 2002).

Inorganic NPs in polymeric membranes is a technique that makes polymeric membranes attractive for commercialization (Khin et al., 2012).

A nanometer-scale metal particle can degrade a wide range of contaminants since their reaction rates are much faster than their microscale and macroscale counterparts. These membranes are chemically functionalized to increase their affinity, selectivity, and capacity to target organic and inorganic solutes and ions in solution (Tuccillo et al., 2012; W. X. Zhang, 2003).

NPs of zero-valent iron is used to remediate groundwater contaminated with chlorinated hydrocarbons, perchlorates (Karn et al., 2009), and drug residues (I. Ali et al., 2020; I. Ali, Alharbi, et al., 2019; Ali, Burakov, et al., 2019; Ali, Rehman, et al., 2019). Contaminants that can be eliminated using nanometal particles include chlorinated ethanes, chlorinated ethenes, pentachloroethane, hexachloroethane, and heavy metals (H. Song & Carraway, 2005). Vidmar et al. (2018) investigated the use of nano zero-valent iron to remediate cadmium from industrial effluent wastewater. The total cadmium concentration in the effluent water was reduced to as low (7 ng L^{-1}). Even after long-term exposure, the Cd^{2+} concentration was below 0.1 µg L^{-1}(Vidmar et al., 2018).

3.3.4 Nanofiber Membranes

Nanofibers are essentially in the range of 1 to 200 nm for ultrafiltration. NFs can be prepared from diverse polymers and therefore have altered physical properties and application potentials. Some natural polymers used for scaffold production are cellulose, collagen, gelatin, keratin, polysaccharides, silk fibroin, alginate, and chitosan. Subsequently, synthetic polymers such as poly(lactic acid) (PLA), poly(caprolactone) (PCL), poly(L-lactide) (PLLA), poly(lactic-co-glycolic acid) (PLGA), polyurethane (PU), poly(ethylene-co-vinyl acetate) (PEVA) and others, including blends, have been developed for incorporation into scaffolds. A wide range of fiber diameters can be synthesized to eliminate particulate matter below 0.1 mm (Khin et al., 2012).

Electrospinning is commonly used to produce NFs due to its straightforward setup, ability to manufacture unbroken NFs from various polymers, and the ability to make ultrathin fibers with controllable orientations, compositions, and diameters (D. Li & Xia, 2004).

Yoon et al. (2006) synthesized poly(acrylonitrile) (PAN) nanofibrous layers reinforced on non-woven microfibrous substrates such as polyethylene terephthalate and applied a water-resistant but a water-permeable layer of chitosan on top of the nanofibrous coating (Yoon et al., 2006).

Likewise, thiol-functionalized mercaptopropyl silica NFs have been prepared by dissolution electrospun PAN nanofibres with dimethylformamide (DMF) and varnishing 3-mercaptopropyl trimethoxysilane through a sol–gel process (Li et al., 2011). Researchers have established that titanate NFs can be used as a sorbent in a permeable packed-bed reactor to eliminate arsenic (Tuccillo et al., 2012).

3.3.5 Nanocomposite Membranes

The nanocomposite membrane is a relatively new combination filtration material consisting of mixed matrix membranes and surface-functionalized membranes. The mixed matrix membranes incorporate nanofillers in a polymeric or inorganic oxide matrix, which increases its efficiency due to the higher surface-to-mass ratio (A. Mishra & Clark, 2013). The use of zeolites as the matrix material increases membranes hydrophilicity, resulting in elevated water permeability.

Other important nanocomposite fillers are nanosilver, carbon nanotubes, and photocatalytic nanomaterials such as the bimetallic NPs and TiO_2 to increase resistance to fouling (Feng et al., 2013). Metal oxide NPs (e.g., Al_2O_3, TiO_2, etc.) also increase thermal and mechanical stability (Gehrke et al., 2015).

Benítez et al. (2009) investigated the removal of phenyl-urease in natural waters using thin-film composite membranes of polypyperazinamide and cellulose acetate polymers (Benítez et al., 2009). It has been shown that the retention of phenyl-urease on the thin film membranes was in increasing order for isoproturon, linuron, chlortoluron, and diuron. This behavior indicates that the molecule polarity is a primary parameter that impacts the contaminants retention in the membrane matrix.

Kim and Deng (2011) reported developing a novel thin-film nanocomposite membrane by incorporating ordered mesoporous carbon as nanofillers into thin-film polymeric matrices (E.-S. Kim & Deng, 2011). The constructed thin-film nanocomposite membranes are semipermeable with a selective coating on the outer surface commonly applied for reverse osmosis.

Graphene, oxide-ferric hydroxide composites, have also been used to eliminate arsenic from water (Chandra et al., 2010; I. Gehrke et al., 2012; K. Zhang et al., 2010) fabricated a microsieve by depositing photocatalytic titanium dioxide NPs on a metallic filter through a dip-coating process.

The surface functionalization prevents the membrane from clogging by oxidizing organic contaminants and preventing fouling layers. The report further states that the antifouling agent and photocatalytic nanocoatings reduce the contaminants at the microsieve surface before the formation of foaming. Another approach highlights bionanocomposite membranes with surface-immobilized selective proteins (R. Srivastava, 2019).

The commercially available QuantumFlux membrane manufactured by NanoH_2O Company, Los Angeles, CA, USA, utilizes the reverse osmosis process. This product is classified as a mixed-matrix membrane and fabricated by adding super-hydrophilic NPs to a polyamide matrix to form a thin-film nanocomposite membrane with advanced permeation efficiency and lower fouling potential (Gehrke et al., 2015). Recent advancements of nanomembranes in wastewater remediation applications are highlighted in Table 4.

3.4 Photocatalytic Nanomaterials for Water Treatment

Photocatalysis, an innovative oxidation process, is applied to wastewater remediation to remove micro-contaminants, microbes, and trace contaminants from water (Gehrke et al., 2015; Tijing et al., 2019; Adhena Ayaliew Werkneh & Rene, 2019). The catalytic features of nanomaterials allow their use as redox-active media for water treatment (Obare & Meyer, 2004).

Table 4 Recent studies on nanomembranes used for wastewater remediation

Types of nanomembranes	Application of nanomembranes	References
SiO_2 loaded tea waste nanocomposite	Removal of Cd^{2+} (222 mg/g) and Pb^{2+} (153 mg/g) from wastewater	(Joshi et al., 2020)
Starch derived hydrogel nanocomposite	Remediation of crystal violet (CV) 2500.0 mg/g and MB dye (1428.6 mg/g) from wastewater	(Moharrami & Motamedi, 2020)
TiO_2- polyetherimide nanofiber membrane	Suitable for water treatment and hindering the growth of *E. coli*	(Al-Ghafri et al., 2019)
Palladium (Pd)/Zeolite (Ze) nanofiber membrane	Adsorption of ammonia in water treatment	(Choi et al., 2016)
Cu-NPs intercalated CNT membrane	Efficient sorption of As^{3+} (90%) in potable water treatment	(Luan et al., 2019)
Graphene oxide amended-bacterial nanocellulose membrane (BNC)	Treatment of organic dyes	(Zhong et al., 2020)
Polymer-cement composite	Removal of tannin (98% photodegradation efficacy) from wastewater	(Baltes et al., 2018)
Sponge-graphene oxide composite	Removal of MB dye (19.60 mg/g) from aqueous media	(Nayl et al., 2019)
2D boron nitride (BN)-nanosheet	Efficient sorption of Cu^{2+} heavy metal ion	(Du et al., 2020)
Polyethersulfone or gelatin derived nanomembrane	Removal of Rhodamine B dye (98%) and effective remediation of textile industrial effluent	(Nasr & Ali, 2022)
Electrospun nanofibre membranes embedded with iron oxide NPs	Oil spill cleaning	(Al-Husaini et al., 2019)
Nanofiltration membrane bonded with m-phenylenediamine	Reactive Red dye removal (98% rejection efficacy) from textile effluent	(Gunawan et al., 2019)
Fe amended montmorillonite nanomembrane	Treatment of mercury (89.4%) contaminated effluent combined with cyanide	(Lodo & Diaz, 2019)
Electrospun polyacrylonitrile membranes embedded with polyaniline	Sorbent material of Pb^{2+} (290 mg/g) and dichromate (1202 mg/g) from wastewater	(N. Mohammad & Atassi, 2021)
Polyethersulfone membrane modified by GO	Enhanced water flux, removal of salts, and heavy metals remediation in the water treatment process	(Marjani et al., 2020)
Amide functionalized graphene nanomembranes	Enhanced ion rejection (As^{3+}, Cu^{2+}, and NO_3^-) performance in wastewater treatment	(Tabasi et al., 2022)
Hollow fiber ceramic membrane	Chromium removal	(Uddin et al., 2021)
Crystalline nanocellulose nanofibrous membrane	Sorption of heavy metals and eco-friendly treatment	(R. K. Mishra et al., 2018)
Composite polymeric membrane	Water distillation with enhanced rejection efficacy and functionality	(Ursino et al., 2018)

The nanocatalysis process involves dispersion of the contaminant, adsorption, reaction on the catalyst surface, followed by desorption of the products which are diffused from the catalyst surface (Tijing et al., 2019; Adhena Ayaliew Werkneh & Rene, 2019).

Titanium dioxide (TiO_2) is a potential photocatalyst for water treatment because of its high extraction efficiency and speedy degradation of organic compounds. The degradation mechanism for organic pollutants involves oxidative and reductive processes (Adesina, 2004). Nano-TiO_2 films have inactivated various microorganisms and degraded cyanotoxins (Tuccillo et al., 2012).

A variety of mesostructured titanium oxide (m-TiO_2) NPs have been synthesized by doping with boron (J. Li et al., 2008), manganese (Shao, 2008), sulfur (Y. Liu et al., 2009), iodine (Su et al., 2009), cobalt (Kuljanin-Jakovljević et al., 2009), iron (H. Yu et al., 2010), carbon (Vu et al., 2012), nitrogen (M.-C. Wang, Guo, et al., 2012; Wang, Lin, et al., 2012) and silver (Suwanchawalit et al., 2012). The elimination of organic carbon from water polluted with organic waste was vastly improved by adding TiO_2 NPs under ultraviolet light's influence (Chitose et al., (2003) (Chitose et al., 2003).

Kabra et al. (2004) explored titanium oxide photocatalyst to remediate water polluted by inorganic and organic contaminants (Kabra et al., 2004). They demonstrated the efficacy of TiO_2 NPs in the degradation of various organic compounds (dioxins, furans, chlorinated compounds, PCBs, etc.) under UV light, and also to reduce the toxicity of metal ions such as Ag(I), Cr(VI) and Pt(II) in aqueous solutions. The formation of visible light-initiated TiO_2 NPs has invoked substantial appeal. It has been shown that N-doped TiO_2 NPs could photodegrade MB under visible light (Adesina, 2004; Obare & Meyer, 2004). Various immobilized TiO_2 devices have been explored for water decontamination by solar photocatalysis.

TiO_2 NPs can eliminate complete waterborne pathogens enlisted by global regulators for human consumption (Acevedo et al., 2012). Li, Wang, et al. (2017) studied the photocatalytic degeneration of MB employing TiO_2 assisted PMMA (poly (methyl methacrylate) nanomaterial under the presence of UV light (Yang Li, Wang, et al., 2017; Li, Zhao, et al., 2017), as shown in Fig. 7.

This nanocatalyst exhibited excellent catalytic activity and regeneration capacity for five cycles. De Voogt (2016) studied Pd/Fe_3O_4 nanocatalysts for dehalogenation in the wastewater remediation process. The catalyst was magnetically re-extractable, remarkably active, high tolerance to organic solvents, and sensitive to the presence of heavy metals like lead and mercury (De Voogt, 2016).

3.5 Bioremediation and Bioreactors

Various biologic agents such as bacteria, fungus, and algae eliminate pollutants and detoxify water. Nanobioremediation is a sustainable technology where microbial cultures, extracts, and biomolecules are

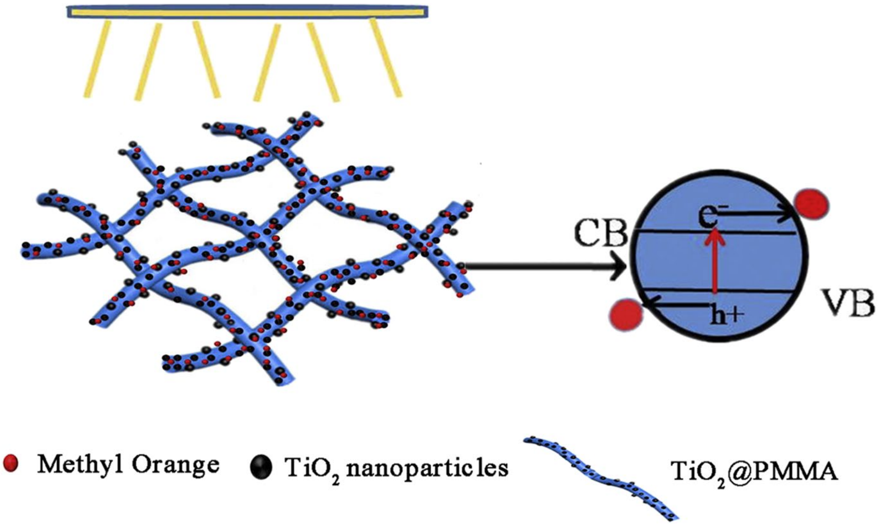


Fig. 7 Photocatalytic assisted degradation of methyl orange (MO) dye by TiO_2/PMMA (poly (methyl methacrylate)) (Copyright Elsevier 2017. All rights reserved reprinted with permission) (Li et al., 2017a; Li et al., 2017b)

employed to produce bio-nano materials for water remediation and treatment (Bhatt et al., 2022). The contaminants produced by the contaminants become the major energy resource in their metabolic pathway (El-Sheekh et al., 2016). Bioremediation can be categorized into two main types: in situ type, where the microorganisms prevailing in the contaminated site are habituated to utilize the organic chemicals for metabolism, and *ex-situ* type, where bioremediation is an aerobic process that involves pumping followed by treatment of the unclean water using a slurry phase system or in bioreactors (Kumar et al., 2015).

The microbial degradation efficiency of pollutants from wastewater is dependent on the nutrient, microorganism, temperature, moisture content, and composition of the contaminants and their biodegradability (de Lorenzo, 2011; Salgot & Folch, 2018). Recently, there has been rising consideration to bioremediation applications such as the de-chlorination of the chloroform($CHCl_3$) and trichloroethylene (C_2HCl_3) and the eradication of polychlorinated biphenyls (PCBs) in the river/stream deposits (Adhena Ayaliew Werkneh & Rene, 2019). Genetically modified microbes such as *Bacillus*, *Streptomyces*, and *Pseudomonas* are increasingly studied for bioremediation of heavy metals.

Werkneh et al. (2018) researched the concurrent bioaugmentation of phenol and selenite from oil refinery effluent using *P. chrysosporium*. They showed that the bioremediation process yielded biogenic, elemental selenium as the end product. Recently exopolysaccharides derived from bacterial end-products were found effective in treating water and soil contaminants, as shown in Fig. 8 (K et al., 2018; Werkneh et al., 2018).

Biodegradation has also been exploited to configure bioreactors for water and wastewater remediation. Biofilm-based bioreactors consist of a packed fixed-bed system employed to support microbial attachment. The attached biofilm biodegrades the pollutants as the wastewater flow through (Kureel et al., 2018). However, nanomaterials can also replace these beds, which act as a filter medium, such as the fluidized bed reactor, anaerobic sludge blanket reactor, and sequencing batch reactor.

Thus effectively integrates the reduction in installation and operational costs and provides high water treatment efficiency (Tijing et al., 2019; Werkneh and Rene, 2019).

4 Challenges and Opportunities

4.1 Challenges

The use of nanotechnology and nanomaterials has opened avenues in wastewater remediation. However, there are challenges in its path. No specific

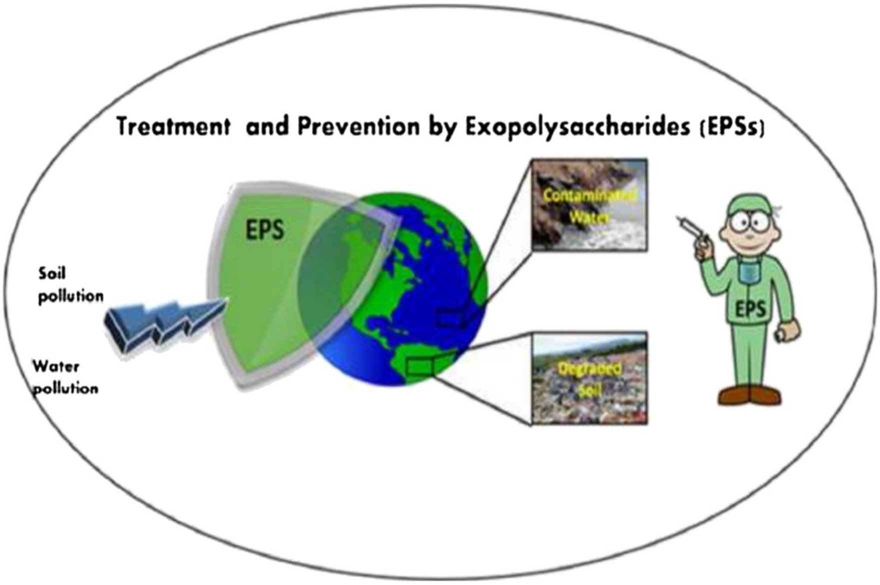


Fig. 8 Exopolysaccharides for remediating water and soil contaminants, (Copyright© Elsevier 2018. All rights reserved reprinted with permission) (K et al., 2018)

or standard nanomaterials and support regulations are needed from the industries, administrators, and related stakeholders to create new laws or modify the existing regulations (Brame et al., 2011).

Although research on nanomaterials for water treatment is conducted to evaluate the potential health risks, including life cycle analysis, toxicity, and dispersion of NPs in water bodies, many such studies have yielded contradictory results due to the lack of generalized standards for experimental investigations and measurements. Presently, there are various laws and regulations globally yet formally incorporated into international laws and regulatory standards (Gehrke et al., 2015).

The basic problem with legal issues is assigning cross-functional nanomaterials to their legal framework. However, based on the report by (Paradise et al., 2009), the European Union and the USEPA have initiated a way to deal with the enforcement of new protocols and guidelines concerning nanomaterials and their exposure into various aqueous water bodies (coastal waters, groundwater, surface waters, and transitional waters) by establishing the European Water Framework Directive through REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) amendments.

Even if nanomaterials present in the water does not have a direct impact on human life, there is a likelihood of absorption of silver NPs (Asghari et al., 2012), titanium dioxide (Asztemborska et al., 2018), and carbon nanotubes (Petersen et al., 2011) through consumption of fish harvested from contaminated water.

Hence, the impact of the various nanomaterials on aquatic life needs attention due to their potential toxicological hazards towards humans and fauna. The contribution of various nanomaterials and challenges faced in wastewater remediation is illustrated in Fig. 9.

Another challenge is that most nanotechnologies for water and wastewater remediation have been studied. Only a few of them are expected to be feasible alternatives to conventional methods due to the enormous financial requirements for start-ups (Brame et al., 2011; Gehrke et al., 2015). Moreover, inadequate knowledge regarding the behavior and fate of NPs on human health and the environment has triggered a toxic panic among the consumers. Since this toxicity is dependent on the chemical and structural properties, any minor change could drastically change its properties (P. P. Fu et al., 2014). The downside is that nanomaterial use may cause reactive oxidative stress that directly or indirectly interacts with organelles to induce DNA damage, cell death, cancer initiation, and apoptosis in eukaryotes (X. Zhu et al., 2013). Full risk assessment of human health and environmental safety requires evaluation. The risk assessments should include exposure, the probability of exposure, eco-toxicological and pathological analysis, and risks related to transport, persistence, transformation, and recyclability (V. Sharma & Sharma, 2013).

4.2 Environmental Concern and Potential Negative Impact of Nanotechnologies in Water

The usage of nanomaterials has certain negative consequences for the ecology and environment. Various nanomaterials are discharged involuntarily into lakes, waterways, and oceans (Adam et al., 2018; M. Chen et al., 2017). Potable water can ultimately be influenced by these nanomaterials as well. As a result, the pollution of water environments resulting from these nanomaterials might be toxic to aqueous life or human life. Table 5 illustrates the functionality and toxicities of often used nanomaterials in aquatic environments.

CNTs are not water-soluble and accumulate in sediments, which is toxic to bottom species in water and affects the movement of other pollutants (B. Song et al., 2018). In research carried out by (B. Zhu et al., 2018), SWCNTs demonstrated a huge influence on the growth of Artemia salina in seawater. With the greater concentration of SWCNTs, greater larval mortality was observed. Da Rocha et al. (2019 investigated the toxicity of CNTs in zebrafish. The neurotransmitters serotonin (5HT) and dopamine (DA) are vital for behavioral reactions and brain processes. The SWCNT intervention increased dopamine and serotonin concentrations by 3 to 6 times, according to experimental results.

Alteration in these neurotransmitters can disrupt various physiological functions and activities that they control. MWCNT affects the DNA repair pathway, according to (Tabei et al., 2019). (Martínez-Paz et al., 2019) molecular larval research at the marine level shows that MWCNTs affect the transcription of target genes in mortality. In the green algae *Raphidocelis subcapitata*, graphene oxide has been shown

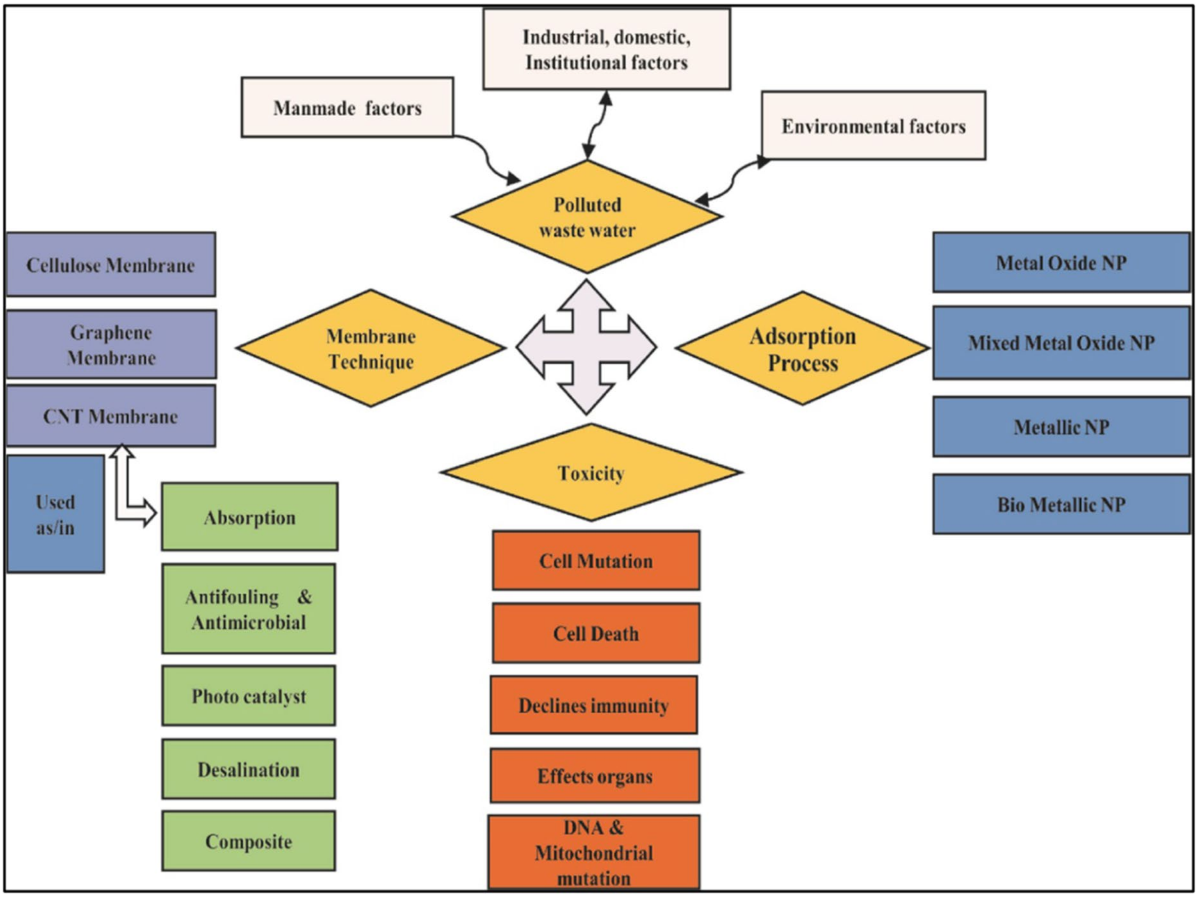


Fig. 9 Nanotechnology contribution in wastewater remediation (Copyright© Elsevier 2017. All rights reserved reprinted with permission) (Deshpande et al., 2020)

to have harmful effects such as the generation of reactive oxygen species and membrane damage and the induction of apoptosis division rates in *Chlorella vulgari* (Hu et al., 2015). Using the *Dunaliella tertiolecta* green alga, (Ouyang et al., 2015) revealed that graphene oxide-quantum dots ingestion is 10–80 times more than nanobased-graphene oxide to enhanced oxidative stress, cell accessibility, and cell proliferation. When exposed to graphene quantum dots at a 200 g/mL concentration in zebrafish embryos, these graphene-derived nanomaterials caused larval activity and embryonic abnormalities (Z. G. Wang et al., 2015).

Silver NPs have been shown to have harmful effects on microorganisms, algal, and fungi. When silver nanoparticles are released from products into an aquatic environment, aquatic species, especially benthic species, are at risk. According to aquatic mesocosm research, silver NPs caused genetic mutations and oxidative damage in *Scrobicularia plana*. These nanoparticles also trigger hepatopancreas disease and *Mytilus galloprovincialis* to develop early mortality (Buffet et al., 2014). *Corbicula fluminea* species facilitated the movement of silver NPs from water to sediment; as a result, significant amounts of silver accumulate in the sediments, posing a threat to benthic species (W. Liu et al., 2018). The biosorption of silver NPs in shells and organs study found that the shells are a better alternative for higher silver nanoparticle concentration markers. In contrast, tissues are becoming particularly sensitive to small levels. Higher silver NPs concentrations may have caused calcospherites breakdown and calcium depletion.

Table 5 The functionality and toxicities of commonly used various nanomaterials in aquatic environments

Sl.No	Nanomaterials	Concentration or Toxicities	Remedial approach	References
1	Nano-zerovalent iron (nZVI)	0.30–1.10 g/L concentration of nanoparticle detected in all tested bacteria	The presence of iron in the aging of nZVI reduced to Fe^{2+} ions, which reduced the contaminants	(Semerád et al., 2018; Y. Xie et al., 2017)
2	Graphene oxide	A higher concentration of graphene oxide, about 500 ppm detected in *Artemia salina* and resulted in hindered growth	adsorption of heavy metal ions along with organic pollutants	(De Marchi et al., 2018; Pretti et al., 2014)
3	Silver NPs	Silver nanoparticle concentration (0.1-2 ppm) restrained biological behavior and metabolic activity of *Corbicula fluminea* species	Silver NPs can adsorb heavy metal ions such as Zn^{2+} and Cu^{2+} in water	(W. Liu et al., 2018; Tao et al., 2016)
4	Nickel NPs	*Labeo rohita* fish was prone to the nanoparticle (25 mg/L) for 21 days. Significant reduction in growth and hemoglobin level were observed	Magnetic hydroxyapatite can be employed as a sorbent to remove Ni^{2+} from water	(Thanh et al., 2018)
5	Chromium oxide NPs	*Labeo rohita* fish was prone to the nanoparticle (25 mg/L) for 21 days. Chromium oxide NPs resulted in fish deaths at earlier stages. Significant reductions in growth and hemoglobin level were observed. There was a remarkable rise in total protein level	Superparamagnetic iron oxide NPs can be employed for Cr_3O_4 removal	(Burks et al., 2013)

Thakkar et al. (2016) investigated the effects of single-walled carbon nanotubes (SWCNTs) on *Dunaliella tertiolecta*, finding that increasing SWCNT concentrations increased the harmful effects on oxidative stress, photosynthetic activity, and growth. In addition, the length, diameter, and framework of CNTs all play a role in the toxic effects of these nanostructures.

As the length of CNTs grows longer, so does the toxicity of this nanomaterial. On the other hand, CNTs have augmented toxic copper effects. Silver nanoparticles in bottom waters may stabilize and create a silver-mercury composite. The creation of mercury-silver amalgams can cause significant colloidal mercury mobilizing in surface water, which can then be transferred across the streams to unpolluted areas. As a result, when mercury-silver amalgam NPs are released into water bodies, they may greatly enhance mercury transportation over longer distances (Tao et al., 2016). Graphene-based nanomaterials will undoubtedly be released into the environment during manufacture, transportation, use, and disposal. When these materials are released into the environment, they will interact with various physicochemical and biologic processes, resulting in significant detrimental impacts on the environment with implications at the ecological level (De Marchi et al., 2018). Several studies have focused on the toxicity of graphene-related nanomaterials in the aqueous system. It has been found that the toxic effects of this graphene-based are based on their surface charge, size, structure, susceptibility concentration, and environment (Sun et al., 2016), as well as the target species, particle route of exposure, medium composition, and exposure duration (Khosravi-Katuli et al., 2017). The aqueous environment's adsorption properties of graphene-derived nanomaterials are crucial when assessing their environmental impact. Because of their higher water solubility and reduced size, these functionalized graphene oxide NPs are extremely difficult to remove from polluted water once heavy metal ions have been adsorbed. Some investigations found that rats ingesting TiO_2 in NP-contaminated water suffered crucial organ damage and DNA damage.

Furthermore, artificial nanomaterials have been linked to several health issues, including lung inflammation, mutagenicity, carcinogenic effects, and circulatory abnormalities (Zielińska et al., 2020). Cimbaluk et al. (2018) investigated the harmful effects of MWCNTs in two marine species, *Astyanax altiparanae* and *Danio rerio*. They discovered the possibility of CNTs-DNA linking, the creation of oxidative stress, and acute and sub-chronic neurotoxic effects in the fish varieties (Cimbaluk et al., 2018).

4.3 Opportunities

Although there are several challenges to sustainable solutions, there is ample scope for new ventures and commercial opportunities for MSMEs. Most conventional methods used for water treatment suffer from drawbacks related to operations, economic benefits, energy requirements, and processing efficiency, limiting their wide-scale and long-term applications (Adhena Ayaliew Werkneh & Rene, 2019). From a technological standpoint, nanomaterials for water and wastewater remediation can offset these limitations.

Nanomaterials have gained an increasing demand due to properties such as antimicrobial activity, large surface area (Durán et al., 2007), chemical stability (Ying Zhang et al., 2018), and photocatalytic activity (Ghosh & Das, 2015). One such enterprise, Altair Nanotechnologies, has developed lanthanum-based NPs that can absorb phosphates from water and prevent algal growth (Mongillo, 2008).

Arsenic remediation techniques are a forefront area for research. Arsenic is employed in pesticides, poultry-food supplements, poisons, and wood preservers. Most arsenic compounds are odorless or tasteless, even in potable water. Nevertheless, the natural arsenic present in the soil can also make the groundwater toxic to humans. Iron oxide NPs can eliminate arsenic by using a magnetic field. The product mesolite has been examined in several countries to remove ammonia from contaminated wastewaters.

After extraction, the surplus ammonia may be reprocessed and used as a fertilizer. A similar process can also be used as a support system for larger wastewater remediation plants. There are reports of an advanced form of reverse osmosis using CNTs, which may minimize the desalination expenditure by 75% compared to conventional methods.

The nanopores of CNTs also lessen the pressure required to force water through the membrane, reducing energy costs. Continuous research is needed to develop innovative technologies to clean up pollutants in groundwater for industrial purposes. Nanotechnology has provided cost benefits and productive remedies to water treatment issues by eliminating several recalcitrant compounds, biofilms, and viruses (Gehrke et al., 2015; Hlongwane et al., 2019; Mongillo, 2008). Advanced nanosorbents, dendrimers, polymers, CNTs, etc., need further research and implementation. Nanosensors are an upcoming technology that can sense contaminants at sub-ppm concentrations (Bethi et al., 2016).

Trichloroethene (TCE) is considered one of the most harmful chemicals due to its pervasiveness and toxicity and comprises 60% of contaminated sites. Tests show that the gold(Au)-palladium(Pd) nanocatalysts can degrade TCE nearly 100 times more rapidly than usual Pd catalysts. One of the significant advantages of this method is that the nanocatalyst directly converts TCE into non-toxic ethane and non-hazardous gaseous hydrocarbons. Tackling nuclear waste is a daunting task. Novel treatment methods using NPs or nanotechnology play a pivotal role in inhibiting nuclear contaminants transfer into the groundwater (Mongillo, 2008). Eroglu et al. (2012) generated a hybrid system where algae were immobilized on electrospun chitosan NFs to abstract nitrates from wastewater (Eroglu et al., 2012). The use of NPs in removing contaminants from the water allows for low energy requirement, simple operation, inexpensive equipment, decreased need for large residential and industrial treatment plants, and to meet universal emission standards, to facilitate large scale production (Lu et al., 2016; Qiao et al., 2014).

Research is ongoing to explore green nanomaterials possibilities for sustainable water treatment such as functionalized silica gel, ionic liquids as green solvents for pollutant extraction, separation processes, periphyton biofilms, and algal biomass (Mishra & Clark, 2013). Innovative techniques such as nanomaterials-based Fenton's catalyst, hybrid nano-membranes, bio-nanotechnology, algal nano-bioreactors, and microbe integrated electrospun NFs are areas that can be further explored and exploited. It is necessary to conduct validation studies under realistic conditions and measure the long-term efficacy of various nanotechnological propositions. Since most nanomaterials present cost is very high, adoption and commercialization depend on focused research on regeneration, reuse, risk assessment, and management (Anjum et al., 2016; Kunduru et al., 2017; Qu, Alvarez, et al., 2013; Qu, Brame, et al., 2013). The integration of various nanotechnologies may provide versatile yet straightforward solutions for different wastewater treatment systems with high efficiency, low cost of operation, multi-pollutant control, and treatment, as reported by a significant number of scientific studies (Dong et al., 2015; Fendrich et al., 2018; Loeb et al., 2019; Matouq et al., 2018; Pi et al., 2018; Qu Alvarez, & Li, 2013; Qu, Brame, et al., 2013).

4.4 Greener Approach for the Large-Scale Use of Nanotechnologies in Water Treatment

Green NPs synthesis is an economically viable and ecologically friendly approach to synthesizing nanostructural materials with variable topologies, morphology, and particle size variations (Khan et al., 2019). Green synthesis methods use plants, microbes, and fungi to produce nanomaterials. It has become a rapidly growing field of research interest due to its less harmful or nontoxic nature, eco-friendly behavior, and low cost of synthesis (Das et al., 2016; S. Gautam et al., 2017; Goutam et al., 2018). Silver NPs were derived from *P. thonningii* leaf extract and applied to remove heavy metals (Mg, Cu, Pb, and Fe) from water/wastewater in a study (Shittu & Ihebunna, 2017). Banerjee et al. (2014) described a green synthesis of silver nanocomposite utilizing *Ocimum tenuiflorum* known as "Black Tulsi" leaves extract for dye effluents treatment. Wastewater treated can be reused for industrial and residential purposes (Table 6).

In terms of effective, secure, harmless, cleaner, and ecologically friendly synthesis, green derived NPs offer a better potential for enhanced pollutant removal capability. In terms of restoration and recyclability, the application insight of nanoparticles in contaminant removal and wastewater remediation cannot be neglected, as these considerations are crucial in the financial analysis of nano-based water and wastewater technology and its long-term economic feasibility (Venkateswarlu et al., 2016). Much research has shown that NPs may be employed as a sorbent material and generate zero contaminants (Srivastava et al., 2017).

Additionally, due to organically surface functional groups of the adsorbent, NPs can produce zero waste, which could eventually decompose after some time. The same characteristics cause NPs to be less recyclable (Lunge et al., 2014).

Srivastava et al. (2017) stated that spherical magnetic NPs with an average diameter of 8.75 nm prepared by co-precipitation utilizing *Lagerstroemia speciosa*

Table 6 Application of green-based NPs in dye treatment and wastewater remediation

Sl. No	Nanoparticles	Biomaterials	Characteristics	Application	References
1	TiO_2	*Jatropha curcas L-leaf extract*	Size:10–20 nm, spherical shape	Treatment of tannery effluent (COD removal, 82.2%; Cr removal, 76.4%)	(Goutam et al., 2018)
2	Fe	Green tea (*Camellia sinensis*)- leaf extract		Color removal-95% and 80%-dissolved organic matter from textile polluted water	(Ozkan et al., 2018)
3	Ag	*Piliostigma thonningii*-leaf extract	Size:50–114 nm, spherical shape	Fe^{2+} removal-96.7%, Cu^{2+} removal- 89.3%, Pb^{2+} removal-97.8% and Mg^{2+} removal-93.5%	(Shittu & Ihebunna, 2017)
4	Au	*Lagerstroemia speciosa-leaf extract*	Size:41-91 nm, hexagonal shape	Photocatalytic reduction of MB, MO, and bromophenol blue dyes with reduction efficacy over 90%	(Choudhary et al., 2017)
5	FeO	*Amaranthus spinosus*-leaf extract	Size:50-114 nm, spherical shape	Color removal in dyes (MO-75.2%, and MB-69.15%)	(Muthukumar & Matheswaran, 2015)
6	Cu	*Citrus grandis*-Peel extract	Size:22-27 nm, spherical shape	Methyl red Degradation efficacy-96.5%	(Sinha & Ahmaruzzaman, 2015)
8	rGO/Fe_3O_4	*Solanum trilobatum*-leaf extract	Size:18 nm; spherical shape	MB degradation efficacy-96%	(Vinothkannan et al., 2015)
9	ZnO	Lemon fruits-lemon extract	Size:21.5 nm, spherical shape	Photocatalytic assisted degradation of (MO, methyl red, and MB) dyes	(Davar et al., 2015)
10	Fe_3O_4	Seaweeds-Algae *Padina pavonica* and *Sargassum acinarium*	Size: *Padina pavonica* (10–19.6 nm) and *Sargassum acinarium* (21.5–27.3 nm)	Bioremediation of Pb using *Padina pavonica*, 91.5%; Pb removal using, *Sargassum acinarium* 78%	(El-Kassas et al., 2016)

bark (LB) extract exhibited substantial Cr^{6+} removal (93.7%) from aqueous medium even after 11 sorption and desorption cycles. Martínez-Cabanas et al. (2016) used *Eucalyptus globulus* plant extract to make FeO NPs in varying proportions of iron and plant extract and found effective in Arsenic adsorption. The regeneration of FeO NPs was carried out by using a moderate level of basic solutions (Martínez-Cabanas et al., 2016).

Cost-effective investigations, which must be conducted to analyze the applicability of nanomaterials synthesis by green method with other traditional products, are attractive, promoting a faster development in nanotechnology (Gutierrez et al., 2017). Formulating guidelines and standards that specify the technical challenges required for successful use in industrial and research development and the products & services offered at commercialized is another crucial step in supporting the industrialization of nanoparticles more effectively (Leech & Scott, 2017). The nanoparticle morphology must be developed, and the synthesis technique must be optimized to retain the longevity of NPs for effective contaminant removal from water and effluents, NP magnetic separability, and the feasibility of reusing. For targeted and various contaminant removal from water and wastewaters, novel NPs containing a greater range of biologic functional groups must be developed by modifying plant metabolism and synthesis approaches (Ali et al., 2017). There are various scientific voids in nanotechnology that, once fulfilled and resolved, could support the treatment of wastewater innovations without endangering the environment or world economies.

5 Conclusion

This review focuses on the contributions of nanotechnology for effective, sustainable, and emerging solutions for the treatment of various wastewater. Nanotechnology in water and wastewater remediation offers opportunities to prevent water contaminations produced by the agricultural, municipal, and industrial activities that the conventional methods have not been able to effectively remove or control due to the presence of co-existing pollutants or multi-pollutants. It has also created a platform for distributing drinking water and quality reusable water for agricultural and industrial uses while demanding low energy consumption. This technology may prove appropriate for developing countries that face poor water quality to meet the increasingly stringent public health, environmental, and food safety standards. Nanomaterials, including advanced green materials-based technology, can enable efficient water treatment systems at a large scale capable of remediating multiple pollutants. This novel technology has opened the floodgates for research and offers an excellent opportunity to increase the effectiveness, robustness, and sustainability of water treatment at the point of use for a healthier and superior life.

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Declarations

Conflict of Interest The authors declare no competing interests.

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