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Review

Advances in Nanoparticles and Nanocomposites for Water and Wastewater Treatment: A Review

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Abstract: Addressing water scarcity and pollution is imperative in tackling global environmental challenges, prompting the exploration of innovative techniques for effective water and wastewater treatment. Nanotechnology presents promising solutions through the customization of nanoparticles and nanocomposites specifically designed for water purification applications. This review delves into recent advancements in nanoparticle-based technologies for water treatment, with a particular focus on their synthesis methodologies, intrinsic properties, and versatile applications. A wide range of nanoparticles, ranging from metal nanoparticles to carbon-based nanomaterials, along with hybrid nanocomposites such as metal/metal oxide-based nanocomposites, polymer-based nanocomposites, and others, were emphasized for eliminating contaminants from water and wastewater matrices. Furthermore, this review elucidates the underlying mechanisms governing pollutant removal processes, encompassing adsorption, catalysis, and membrane filtration, facilitated by nanoparticles. Additionally, it explores the environmental implications and challenges associated with the widespread deployment of nanoparticle-based water-treatment technologies. By amalgamating existing research findings, this review provides valuable insights into the potential of nanoparticles and nanocomposites in mitigating water-related challenges and presents recommendations for future research trajectories and technological advancements in this domain.

Keywords: nanomaterials; nanosorbents; nanocatalysts; wastewater treatment; metal nanoparticles; nanocomposites

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1. Introduction

Water is a vital natural resource necessary for the survival of all life forms on Earth. Its cleanliness is essential for sustaining life in all its forms. However, water pollution poses a worldwide challenge, stemming from various sources. These consist of improper sewage management, industrial-waste release, marine pollution, the unsafe handling of radioactive substances, and specific agricultural methods [1,2]. Water pollution harms the economic growth and societal values of different countries. A report by the UN has recently stated that the availability of freshwater is becoming a global challenge in the 21st century [3,4]. Emerging pollutants found in wastewater streams typically consist of chemical substances that exhibit nonbiodegradable properties, persisting within the environment over time.

These pollutants can spread throughout the food web, presenting potential risks to both human health and environmental ecosystems. Also, they pose threats to the flora–fauna and other organisms inhabiting these environments [5–7]. Research is still going on worldwide to find better ways to improve the quality of water that should also be cost-effective [8,9].

The fundamental methods of wastewater treatment involve four major steps: preliminary, primary, secondary, and tertiary treatment [10]. Preliminary treatment is the most important step. This step claims to remove larger particles, such as plastics, which might cause blockages in the pipes and hamper the rest of the process. They contain metal screens to filter out these large particles. Solid materials like sand, grit, and stones are further segregated by sedimentation. And if there are still certain particles left, then they are removed by floatation. The primary treatment removes most of the suspended solids by using clarifiers. To treat the primary sewage sludge, usually mechanical means are used, or else they are treated in a different part of the plant [11,12]. Coagulants are often used in this step for treating the suspended solids [13]. To remove the pathogens, pharmaceuticals, and dissolved solids, secondary treatment is required. This step involves biological treatment methods such as sequencing batch reactors (SBRs) that consist of two tanks [14]. Then, the concluding phase is the tertiary treatment, and this step includes the removal of pathogens, odors, and nutrients [15–17]. All these treatment methods have shown great success for long periods, but using them on a large scale poses a sea of challenges. Newer and unique contaminants are emerging every day, which need new technologies that can effectively work on them.

One approach to addressing water pollution involves utilizing nanotechnology [18]. Nanotechnology-based methods for treating wastewater leverage cutting-edge techniques and materials to cleanse polluted water. This process uses nanoparticles or other nanoscale substances to eliminate pollutants like inorganic substances, organic substances, and pathogens. By improving filtration and adsorption, nanotechnology provides an innovative solution for attaining a high water quality and safer water for diverse applications. This method employs various nanoparticles to decontaminate water effectively. Nanotechnology is especially successful in removing toxic metals from water sources [19,20]. Using nanotechnology comes with a handful of benefits, including a better operating efficiency, the capability of getting reused, and low expenses [21]. Owing to their unique and exclusive features such as a compact size, large surface area, better mechanical stability, reactivity, strong solution mobility [22], hydrophilicity, hydrophobicity, and dispersibility, they are proven to be a superior option [23–25]. To treat the effluents and improve the quality of water, the size-dependent property of the nanomaterials proves to be very effective [26]. Heavy metals including Pb, Mo, etc.; organic and inorganic pollutants; and harmful microbes can be eliminated very efficiently using the various nanomaterials [27–29].

This review comprehensively explores the progress made in the utilization of nanomaterials for wastewater treatment, with a particular emphasis on the application of metal/metal oxide nanoparticles and carbon-based nanomaterials, including nanotubes, graphene-based nanosheets, fullerenes, and their composites. Additionally, this review discusses various water treatment techniques based on nanotechnology. Furthermore, it addresses different water pollutants and provides a summary of recent advancements in water and wastewater treatment technologies employing various nanomaterials.

2. Nanotechnology-Based Wastewater Treatment Techniques

2.1. Nanomembranes

A special kind of membrane called a nanomembrane is created using various nanofibers and is used to remove undesirable nanoparticles from the liquid medium. This method operates with rapid elimination, prone to agglomerated fouling, and resembles a reverse osmosis process [30]. Mostly, polymer-based membranes are used to produce diverse nanomembranes. In water treatment, water-porous membranes are used that can perform reverse osmosis, ultrafiltration, nanofiltration, and so on. The membrane consists of a porous substrate with a composite layer. This composite layer consists of a carbon-based

substance dissipated into a polymer matrix. One such example is that of carbon nanotubes, which include anti-microbial properties that can reduce mechanical failures by decreasing biofilm formation and fouling [31]. Silver is also doped with a polymer that further produces a polymeric membrane that shows anti-microbial properties [32,33].

Nanomembranes are also employed in wastewater treatment owing to their possession of numerous characteristics that render them particularly advantageous. These include high-level uniformity, homogeneity, optimization, and efficiency, a quick processing time, the ease of handling, and a significant reaction order, making them a preferred choice in this application [34]. The synthesis of stationary membrane nanoparticles can be conducted using hydrogen peroxide to generate ions of free radicals, which can then be utilized to eradicate organic pollutants containing chlorides from real groundwater. This method is often proven as very efficient in industrial and commercial usage [35]. Nanomembranes are mostly used for removing toxins from water bodies. Nanomembranes offer distinct advantages over traditional filtration methods. Unlike traditional approaches, where calcium and magnesium necessitate another ion for compensation, typically, sodium ions are used as an exchanger. However, with nanomembranes, such substitution becomes unnecessary [36,37].

Nanofiber membranes are used in prefiltration, ultrafiltration, separating filtration devices, water handling, and filter cartridges due to their properties, such as strong permeability, bactericidal properties, and excellent porosity [38]. Nanocomposite membranes have properties like excellent water permeability, thermal and mechanical stability, high hydrophilicity, and high fouling resistance [39]. For ultrafiltration, major self-assembling membranes are used, as they have homogeneous nanopores membranes [40]. Aquaporin-based membranes have improved ionic selectivity; hence, they are very effective for treatment in lower-pressure desalination [41]. For the removal of color and odor, and to reduce hardness, nanofiltration membranes are used widely [42]. There are certain limitations to the effective working of the nanomembranes. To overcome these challenges, the selectivity of the nanomembrane should be focused upon. To avoid fouling the resistivity of the nanomembranes, this should be upgraded [43].

2.2. Nanophotocatalysts

Nanophotocatalysts find widespread application in wastewater purification due to their ability to augment catalyst reactivity. This is attributed to their higher surface-area-to-volume ratio and shape-dependent characteristics [44]. Nanophotocatalysts have a crucial impact in expanding the oxidation ability, which works towards the elimination of pollutants by effectively producing the oxidizing species at the surface of the material [45]. Nanophotocatalysts find their application in decomposing harmful organic pollutants. The photocatalytic degradation mechanism involves the following steps: [a] photocatalyst activation, [b] the generation of e−/h+, [c] ion formation in water, [d] the ionosorption of oxygen, [e] superoxide protonation, and [f] the degradation of pollutants [25] (Figure 1). Effluents like azo dyes, chlorpyrifos [46–48], nitroaromatics, organochlorine pesticides, etc., are treated using nanoparticles like semiconductors, zero-valence metals, etc. [49]. Nanophotocatalysts like ZnO, SiO_2, Al_2O_3, TiO_2, etc., are widely used [50–52]. Among other nanoparticles, TiO_2 nanoparticles are proven to be an excellent nanophotocatalyst, as they are highly economical, non-toxic, readily accessible, and chemically stable. The anatase form of TiO_2 is considered a better nanophotocatalyst material [53]. ZnO is known for its efficient work in eliminating the effluents and reusing the water [54–58]. ZnO nanoparticles combined with Pd have been used to treat wastewater and remove *E. coli* due to their strong photocatalytic reactivity [59]. Nanophotocatalysis is further divided into two states: homogeneous and heterogeneous. Heterogeneous photocatalysis is widely used in modern times for the decontamination of water. Heterogeneous photocatalysis necessitates the earlier creation of an interface that links a solid photocatalyst (semiconductor or metal) and a liquid (including reactants and reaction products) [60,61]. The use of nanophotocatalysts has proven to be a highly effective and efficient method for water purification and has

served an essential role in the removal of harmful organic compounds at 25 °C. [62]. The primary benefit of nano-sized materials stems from the nano-dimensional effect, which amplifies the energy bandgap and diminishes the particle dimensions [63]. Furthermore, photodegradation as a process offers numerous advantages including a low cost, reusability, and typically achieving complete degradation. Nanophotocatalysts have a wide range of applications across various fields due to their ability to initiate chemical reactions under light irradiation (Figure 2). Despite notable progress, nanophotocatalysts face challenges such as toxicity and the retrieval of catalysts from mixtures. These issues limit the applications and potential of nanophotocatalysts on larger scales [64].

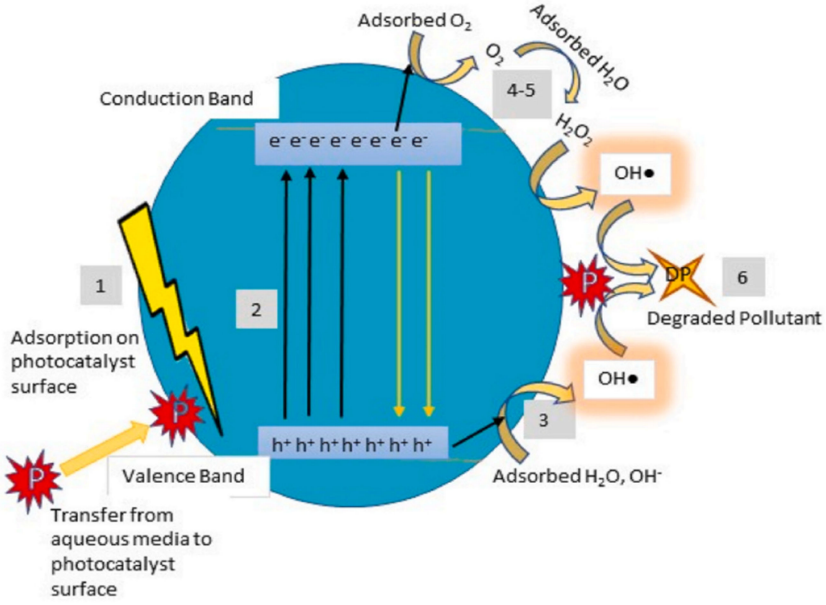


Figure 1. Mechanism of toxic organic compound degradation through nanophotocatalysts. Reprinted with permission from [25].

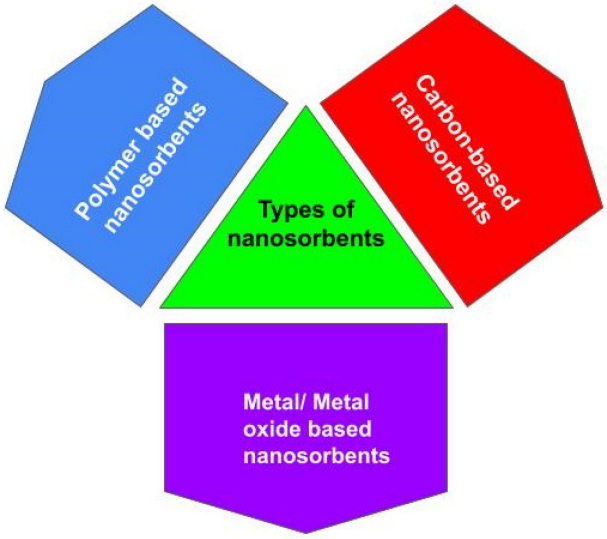


Figure 2. Different types of nanosorbents.

2.3. Nanosorbents

Due to high sorption capabilities, nanosorbents are excellent materials for water treatment [65]. Some of the widely known nanosorbents are carbon-based, polymeric, and metal/metal oxide nanoparticles (Figure 2) [66]. Nanomaterials have garnered significant attention for their role as sorbents in addressing ecological concerns, particularly in the

decontamination of wastewater. This increased interest can be attributed to their notable physicochemical properties, which offer unique advantages in pollutant removal processes. These characteristics set them apart from more typical, conventional sorbents in a number of disciplines. For an optimal sorbent to efficiently treat pollutants within a brief duration, it must possess a substantial surface area, rapid adsorption rate, and specific adsorption and equilibrium times. Nanomaterials have attracted attention due to their nano-scale dimensions, which enable rapid adsorption rates and shortened treatment times, akin to nanosorbents. Moreover, nanoparticles as nanosorbents can serve as a separation medium in water purification to eliminate organic and inorganic pollutants from polluted water [67].

Composite materials comprising various components, such as Ag/polyaniline, Ag/carbon, C/TiO_2, etc., play a crucial role in mitigating the toxicity effects in the wastewater treatment process. Among these materials, carbonaceous substances like carbon nanotubes exhibit remarkable properties. CNTs, which exist as single-walled or multi-walled nanotubes, depending on the synthesis method, possess a cylindrical nanostructure that imparts significant adsorption capabilities. Their efficiency in pollutant removal through adsorption processes is due to their large surface area and numerous available adsorption sites. To maximize the adsorption potential of CNTs, it is important to stabilize them and prevent aggregation, as this can decrease the number of accessible surface active sites. Similarly, polymeric nanosorbents like dendrimers display functional attributes for eliminating organic pollutants and heavy metals from the polluted water. These materials possess distinctive characteristics such as a high surface area, functional groups, and adjustable properties, enhancing their efficacy in pollutant removal procedures [68].

Different nanosorbents show different treatment functions, such as carbon-based nanosorbents efficiently removing nickel ions [69], metal oxides eliminating various heavy metals [70], polymeric fibers being used for treating arsenic and other toxins present in aqueous medium [71], and nanoclays being used for removing hydrocarbons and dyes [72]. Magnetic nanosorbents are an essential component of water treatment systems and a special tool for eliminating various organic contaminants [73]. Organic contaminants are also effectively removed through magnetic filtration processes. Magnetic separation nanosorbents are created by layering ligands onto magnetic nanoparticles, providing them with a particular attraction for target pollutant [74]. There have been numerous reports of ways to regenerate these nanosorbents, including cleaning agents, ion exchanges, magnetic forces, etc. These regenerated nanosorbents have the potential to be more commercially viable and cost-effective. However, carbon-based nanomaterials still pose certain health concerns. Research indicates that toxicity levels are influenced by surface modifications, chemical stabilizers, and nano adsorbents [75,76]. Thus, there is an enormous need to find an alternative for the treatment of water and produce some new adsorbents with reduced toxicity [77].

2.4. Nano and Micromotors

Recently, nano/micrometers have emerged as promising solutions to tackle environmental challenges like water pollutant treatment and environmental monitoring/sensing. They have been extensively employed to achieve distinctive objectives by transforming energy into force for use in machines. They have a variety of applications and can operate either with or without fuel (electric fields, acoustics, and magnetic fields) [78]. They have some exclusive properties like more power, a higher speed, a self-mix ability, unique control movement, etc. [79]. These nano/micrometers are valued for their distinctive characteristics, particularly reactive nano-based materials, which boost their effectiveness in converting toxic pollutants to their non-toxic forms. Nanomachines provide unique benefits when compared to conventional remediation agents due to their small size and ex situ nano-remediation approaches. Additionally, nano/micromotors can reduce both the cleanup time and overall cost associated with environmental remediation efforts [80].

Conventional treatment methods often rely on diffusion alone, requiring external agitation to enhance the wastewater treatment process. However, nano/micrometers offer

a potential solution to overcoming diffusion limitations by utilizing their self-propulsion capabilities to achieve energetic mixing. This ability allows nano/micrometers to effectively break through diffusion boundaries, significantly enhancing water treatment efficiency. By leveraging their self-propulsion, these nano/micrometers can contribute to improved water decontamination efficiency by interacting with the nano/microstructure of materials, thereby increasing the surface area and promoting active processes [81–84]. Au/Pt nanomotors are used for the detection of silver ions using a silver-induced acceleration mechanism [85]. Seah et al. reported that for oil remediation, polymer-capsule motors are very effective [86]. Hydrazine can be detected by the speed–concentration dependence mechanism of Ir/SiO_2 Janus motors [87].

2.5. Nanoparticles for Water Disinfection

Effective infection control necessitates reducing the microorganisms on both interior and exterior surfaces to levels considered safe through the implementation of chemical and physical techniques [88]. Conventional techniques, including ozone, chlorine, reverse osmosis, chlorine dioxide, hypochlorite, and chloramines, are used extensively for disinfection purposes [89–91]. Ozone, chlorine, and its derivatives such as chlorine dioxide and chloramines are commonly used as chemical disinfectants to manage pathogens. Chlorination has been used for a long time and works efficiently against microorganisms. Ozone is proven to be a powerful disinfectant and has no residual effect. On the other hand, ultra-violet light is also used for these purposes [92]. However, these methods are either costly or require a massive amount of energy [93,94]. Hence, the need for alternative techniques is necessary for the disinfection process, which should be timesaving, cost-effective, and sustainable [95]. Due to their large surface areas and better reactivity, nanomaterials have exceptional usefulness for inactivating viruses in water, which is not possible with traditional approaches [96]. Various nanomaterials, including silver (Ag), zinc oxide (ZnO), copper oxide (CuO), carbon nanotubes (CNTs), and polymeric nanoparticles, have been designed to manage infection in wastewater [97–102].

3. Nanomaterials for Water and Wastewater Management

Nanomaterials present promising solutions for wastewater treatment owing to their distinctive properties and remarkable efficiency in removing pollutants. Among these materials are nanoparticles, nanocomposites, and carbon-based nanomaterials, all characterized by their amplified surface area and reactivity. These traits render effective adsorbents and catalysts for eliminating contaminants from wastewater streams without relying on harmful chemicals or excessive energy consumption. Due to their small size and large surface area to volume ratio, they are often considered the best option for wastewater treatment [103,104].

3.1. Applications of Metal/Metal Oxide Nanoparticles in Water Treatment

Metal oxide nanoparticles are derived from metal as starting materials and hold considerable significance across various disciplines, including chemistry, material sciences, and physics. These nanoparticles are formed through thermal processes that enable the formation of a diverse array of oxide compounds, each capable of adopting numerous structural geometries with varying electronic properties, ranging from insulator to semiconductor to metallic. Moreover, these nanoparticles exhibit distinctive opto-electrical characteristics, owing to their nanoplasmonic properties. Particularly, noble metals and alkali nanoparticles like Au, Cu, and Ag demonstrate broad absorption bands within the visible electromagnetic spectrum. In modern materials research, the synthesis of metal nanoparticles highlights the significance of controlling factors like size, facet, and shape to attain desired properties and functionalities [105]. In this review, we have considered some of the widely used metal/metal oxide nanoparticles for the treatment of wastewater.

3.1.1. Iron Oxide

Over the past few years, iron oxide nanoparticles have achieved extensive utilization in the elimination of heavy metals. Iron oxide nanomaterials exhibit remarkable properties, including enhanced membrane characteristics, an elevated surface area, superior tensile strength, and a diminutive particle size [106]. The antibacterial qualities of iron nanoparticles, especially zero-valent iron nanoparticles, were demonstrated in the work by Daniel et al. [107]. The study demonstrated the antibacterial activity of these nanoparticles against *B. subtilis*, *Pseudomonas fluorescens*, and Gram-negative *E. coli*. Magnetic maghemite (y-Fe_2O_3), non-magnetic hematite (α-Fe_2O_3), and magnetic magnetite (Fe_3O_4) are frequently exploited as nano adsorbents. Due to the small size of nanosorbent materials, recovering and separating polluted water presents significant challenges for water treatment. Conversely, Fe_3O_4 and y-Fe_2O_3 can be readily extracted and recovered from the solution. Both have been successfully utilized as sorbent materials for extracting various heavy metals from wastewater [108,109]. Because of their high adsorption capability, enhanced stability, ease of separation, low cost, and magnetic characteristics, iron oxide nanoparticles are also potential options for pollutant removal in wastewater treatment processes. Iron oxide nanoparticles are also reported to be used as an adsorbent of heavy metals (Pb, Zn, Hg, Ni, Cd, and Cr), which are highly toxic even at low concentrations because they exhibit harmful effects on plants and animals and human beings [110,111]. Nanoparticles containing iron oxides have been engineered to tailor their adsorption properties by utilizing various ligands. Some of the ligands used are L-glutathione, ethylenediaminetetraacetic acid (EDTA), α-thio-ω-(propionic acid) hepta(ethylene glycol) (PEG-SH), mercaptobutyric acid, and meso-2,3-dimercaptosuccinic acid [112], as well as polymers such as copolymers of crotonic acid and acrylic acid [113].

Sawafta and Shahwan reported the removal of methyl blue from water and a mixture of water and ethanol using zero-valent iron particles [114]. Nanomaterials based on Fe have exhibited exceptional sorption capabilities owing to their notable attributes, including great permeability, high surface-to-volume ratio, and robust magnetic behavior. These properties collectively contribute to an extraordinary sorption capacity [115,116]. Iron-based nanoparticles have drawn a lot of interest recently due to their high pore volume, high Brunauer–Emmett–Teller Theory (BET) surface area, and supermagnetic characteristics [117]. Singh et al. have innovatively developed supermagnetic Fe_3O_4 nanoparticles for the efficient removal of dyes from wastewater. Their research showcases the remarkable adsorption capabilities of these nanoparticles, which are attributed to their high surface area and magnetic properties. By harnessing the magnetic responsiveness of Fe_3O_4, the nanoparticles can be easily separated from the treated wastewater using a magnetic field, enabling the convenient and cost-effective removal of dyes. This approach offers a promising solution for addressing dye pollution in wastewater, highlighting the potential of Fe_3O_4 nanoparticles in environmental remediation applications [118]. It is noteworthy to highlight that these nanoparticles are used in various oxidation-based treatment techniques, including ozone-, hydrogen peroxide-, and UV-based treatment methods. One effective approach is catalytic ozonation, which integrates ozone with NPs and has proven to be highly efficient for the degradation of compounds like phenacetin [119].

3.1.2. Silver Nanoparticles

Silver nanoparticles are known to exhibit good antimicrobial characteristics. They show high toxicity towards *E. coli* but are moderate towards animal cells under specific concentrations. Silver nanoparticles also play a vital role in the disinfection of water. Various methods are reported for synthesizing these nanomaterials, influencing nanoparticle size and shape [120].

Silver oxide nanoparticles exhibit spherical or faceted shapes, characterized by an extensive surface area and magnetic nanotechnology properties. Usually, the particle size of silver oxide nanoparticles varies from 20 to 80 nm, with a corresponding surface area ranging between 10 and 50 m^2/g. These nanoparticles are offered in different forms, such as

coated, dispersed, high-purity, ultra-high purity, and transparent variants. Moreover, they can be integrated into the manufacturing process of nanofluids, which generally entails suspending nanoparticles in a solution utilizing surfactants or surface charge technology. In addition to silver oxide nanoparticles, other nanostructures such as nanohorns, nanocomposites, nanorods, nanopyramids, and nanowhiskers are also commonly found. Silver oxide nanoparticles stand out for their remarkable antibacterial effectiveness, which has led to extensive research and utilization in various commercial products. They are among the numerous nanomaterials recognized for their antibacterial characteristics [121,122].

An aggregation of silver oxide nanoparticles was designed by Jiang et al. The synthesis demonstrated an exceptional photocatalytic performance in both artificial and natural light. The findings revealed the degradation of methyl orange entirely in 40 min when exposed to artificial visible light, artificial UV light, and sunshine [123]. Baker et al. reported the antimicrobial efficacy of silver nanoparticles using an *E. coli* strain. The experiment involved mixing the nanoparticles with *E. coli* and spreading the mixture onto agar plates. Additionally, plates containing silver nanoparticles were prepared, onto which the *E. coli* was also spread for further analysis [124].

In a study by Shah et al., fresh leaf extract of Paeonia emodi was used as a reducing agent during the synthesis of Ag_2O nanoparticles. The synthesized nanoparticles demonstrated a reduction of 97.78% in methylene blue within a 180 min timeframe. Additionally, the antibacterial effectiveness of the Ag_2O nanoparticles was assessed against both Gram-positive and Gram-negative bacteria. It was observed that the synthesized Ag_2O nanoparticles demonstrated potent growth inhibition against Gram-negative bacteria [125].

Silver nanoparticles have shown efficacy in eradicating over 700 microorganisms present in wastewater treatment plants. They target microorganisms through multiple mechanisms, reducing the likelihood of mutation and resistance development. Even at low concentrations, silver nanoparticles exhibit significant effectiveness. Specifically, silver ions released from the nanoparticles bind to the DNA of microorganisms, inhibiting their ability to uptake essential transport mechanisms such as salt and phosphorus [126].

Ag_2O nanoparticles were produced by Manikandan et al. [127], utilizing root extract from Ficus benghalensis. The synthesized nanoparticles showed exceptional antibacterial properties against lactobacilli and streptococcus mutans. Vithiya et al. [128] synthesized Ag_2O by using *Bacillus thuringiensis* SSV1. The resulting nanoparticles were spherical and monodispersed, and demonstrated inhibitory effects with Gram-positive *Staphylococcus aureus* and Gram-negative *E. coli*, *Pseudomonas aeruginosa*, *Proteus mirabilis*, and *Enterococcus faecalis*. The reduced size of the nanoparticles enhanced their surface area, which helped the organic materials in the water sample be absorbed more effectively. A significant and contemporary development in the use of AgNPs is the hybrid application of various polymers and nano-silver, which has proven to be a successful heavy metal removal technique [129].

3.1.3. Titanium Nanoparticles

Titanium dioxide (TiO_2) nanoparticles exhibit strong photoactivity, low toxicity, and inexpensive semiconductor qualities, which have made them one of the most promising photocatalysts for the purification of water [130]. Due to their low selectivity, TiO_2 nanoparticles can be used to break down a wide range of contaminants, including heavy metals [131], chlorinated organic compounds [132], polycyclic aromatic hydrocarbons [133], dyes [134], pesticides, cyanide [135], and phenols [136]. The photocatalytic capabilities of these nanoparticles enable them to eradicate a broad variety of microorganisms, including viruses, algae, fungi, protozoa, and Gram-positive and Gram-negative bacteria [137].

In recent years, TiO_2 photocatalysts have become a leading option for environmental applications, showing considerable potential in purifying water and air. They excel in breaking down volatile organic compounds and mineralizing undesirable chemical substances found in both water and air streams [138]. TiO_2 nanomaterials have low toxicity to humans, strong chemical and thermal stability, and are comparatively less expensive than

any other nanomaterial [139]. In addition to their photocatalytic properties, photocatalysts find extensive use in wastewater treatment and anti-biofouling applications. TiO_2 nanoparticles offer significant advantages due to their indefinite lifespan [140]. Kiwi et al. examined the photocatalytic peroxidation of *E. coli* cells, peptidoglycan, lipopolysaccharide, and phosphatidylethanolamine from *E. coli* membrane walls using attenuated total reflectance (ATR)-FTIR spectroscopy on TiO_2 [141].

Madani et al. [142] described two membrane preparation methods involving TiO_2. In the initial method, principles of green chemistry were utilized, incorporating a weight percentage of 0.05. A definite percentage of TiO_2 was introduced into the acrylic acid monomer. Subsequently, an initiator and a cross-linking agent were added to this reactive solution. Polyvinylidene difluoride membranes were then immersed in this solution, following the same procedure as the first method [143]. Youssef et al. reported the synthesis of TiO_2 nanowires using hydrothermal techniques. The synthesized nanoparticles were utilized to remove Pb^{2+}, Cu^{2+}, Fe^{3+}, Cd^{2+}, and Zn^{2+} heavy metal precipitates from wastewater [144]. Engates et al. fabricated TiO_2 nanomaterials as a substrate for the removal of multiple metals (Ni, Cu, Zn, Pb, and Cd) [145]. Various studies report the doping of TiO_2 using metal ions such as V, Zn, Cr, Mn, Al, Co, Fe, Ni, Ag, Au, Pt, Pd, and Bi for wastewater treatment. This doping aims to decrease the band gap energy of TiO_2 and shift its absorption from the UV region, thereby significantly enhancing the efficiency of UV light photocatalysis [146].

3.1.4. Zinc Oxide

ZnO nanoparticles can be synthesized using various methods, which broadly fall into three categories: physical, biological, and chemical techniques. Physical synthesis includes laser ablation, physical, chemical, solid–vapor deposition, and high-energy ball milling. The biological synthesis is categorized into microbe-mediated, waste material, and plant-mediated methods [147].

Baruah et al. extensively studied photocatalysis using ZnO nanoparticles to facilitate the oxidation of contaminants [148]. Gondal et al. studied the effect of photocatalysis via ZnO to treat infected water. ZnO is synthesized from compounds like $(NH_4)_2CO_3$ and Zn $(NO_3)_2$. The ZnO produced as a result has a particle size of 20–40 nm. Enhanced photocatalytic efficiency, resulting in elevated rates of bacterial decay, has been attributed to the reduced particle size, which stimulates the production of reactive oxygen species ZnO [149].

Zhang and collaborators investigated and evaluated the characteristics, dispersibility, and water stability of commercially available metal oxide nanoparticles including Fe_2O_3, ZnO, NiO, and SiO_2. The properties of metal oxide nanoparticles are influenced by their interaction with various aqueous environments or their inherent physical characteristics [150].

Motshekga et al. [151] engineered a nanocomposite by integrating silver and ZnO nanoparticles supported on bentonite, subsequently dispersing them in chitosan. The antibacterial properties were assessed using *Enterococcus faecalis* bacteria. The resulting bentonite–chitosan nanocomposites, infused with silver and ZnO, displayed remarkable antibacterial effects. Notably, ZnO demonstrated exceptional antibacterial activity, achieving a removal efficiency of 78%. The antibacterial efficacy of the nanoparticles is impacted by the concentration of bacteria.

Esmailzadeh et al. [152] reported the development of nanocomposites fabricated through the amalgamation of low-density polyethylene and ZnO. The antibacterial efficacy of the nanocomposites was evaluated for their efficacy against *Bacillus subtilis*, a bacterium frequently associated with food spoilage, and *Enterobacter aerogenes*, a bacterium commonly present in both food and water.

ZnO nanoparticles possess potent antibacterial properties, primarily through the generation of reactive oxygen species (ROS) upon their interaction with moisture or biological environments, inducing oxidative stress and damaging bacterial proteins, DNA, and membranes. Additionally, ZnO nanoparticles disrupt bacterial cell membranes, leading to the leakage of cellular contents and a loss of viability. Furthermore, the release of Zn^{2+} ions from the nanoparticles interferes with bacterial metabolic processes and enzyme activities,

contributing to bacterial death. Moreover, ZnO nanoparticles may induce apoptosis in bacteria, activating specific cellular responses that lead to programmed cell death. Overall, the multifaceted mechanisms, including ROS generation, membrane disruption, ion release, and the induction of apoptosis, collectively account for the antibacterial efficacy of ZnO nanoparticles, and are shown in (Figure 3) [153].

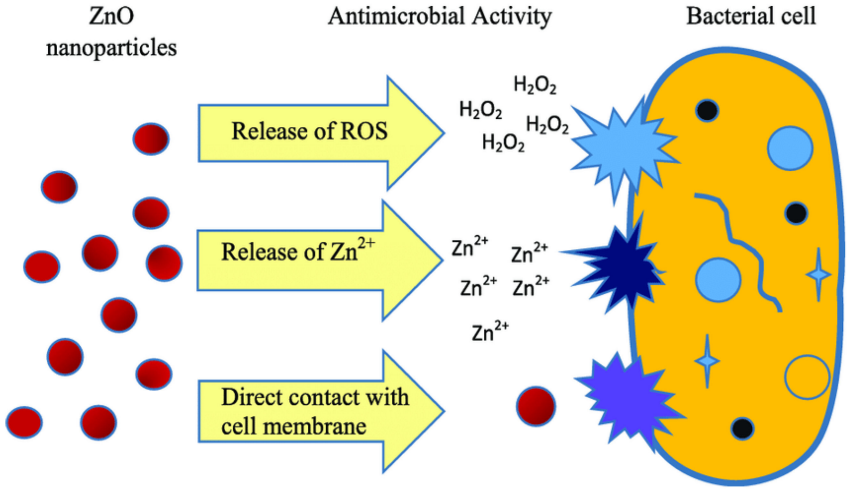


Figure 3. Mechanism showing the antibacterial properties of ZnO nanoparticles. Figure is obtained from [153] and reused under a Creative Commons license.

3.1.5. Copper Nanoparticles

The antimicrobial properties of copper nanoparticles extend to both Gram-positive and Gram-negative bacteria. Ruparelia et al. investigated the antimicrobial effects of silver and copper particles on *E. coli*, *S. aureus*, and *Bacillus subtilis*. Copper exhibited superior antibacterial activity in inactivating *B. subtilis*, while silver nanoparticles surpassed copper in preventing the growth of *E. coli* and *S. aureus* [154]. Studies conducted by Suleiman et al. explored antimicrobial studies using synthesized copper oxide nanoparticles, both in their pure form as well as surfactant-stabilized form. The synthesized nanomaterials displayed a rod-like morphology with an average size of 7 and 12 nanometers. The concentration of the nanoparticle, size, pH, and temperature were varied for the studies. The best antibacterial activity was reported with nanoparticles with an average size of 11.4 nm, and the least significant was found in nanoparticles with an average size of 12.4 nm [155].

Besides their antimicrobial characteristics, which are less potent than silver, copper nanoparticles serve as enhancers of the surface area and pore volume of polymeric beads. These beads are commonly utilized as substrates for nanoparticle integration in large-scale applications [156]. Simultaneous applications of Cu and Ag nanoparticles in wastewater treatment can enhance access to various bacteria. Similar to silver, the probable mechanism of inactivation involves the combination of Cu nanoparticles with the -SH groups present in key microbial enzymes [157]. Many studies have found that Cu nanoparticles can change the physicochemical properties of the activated sludge at very high concentrations. Chen et al. reported a reduction in the flocculation capacity of the activated sludge when concentrations of Cu nanoparticles ranging between 30 and 50 mg/L were used [158]. Copper-containing nanoparticles, like $CuFe_2SO_4$ NPs, have been widely applied in water treatment. Particularly, when combined with other materials as surface coatings, they enhance absorption capacities and facilitate photodegradation processes [159].

3.1.6. Other Metal/Metal Oxide Nanoparticles

Gold nanoparticles have promising applications in environmental analysis, such as chemical sensing and imaging tasks. The optical sensing methods for detecting toxins, and environmental pollutants, make use of Au-based nanoparticles [160–167]. AuNPs are also employed to enhance the performance of electrochemical sensors, owing to their cat-

alytic properties. Electrochemical sensors are extensively researched for their applicability in screening environmental pollutants. Typically, in these methodologies, electrodes are initially modified with AuNPs to augment their surface area for analyte absorption. Additionally, AuNPs catalyze the reduction of analytes, facilitating the generation of electrical readout signals [168].

Biogenic Pd is also widely used to remove micro-effluents and pesticides by dehalogenation methods [169–172]. Nanostructured tungsten oxide (WO2) has demonstrated a remarkable adsorption capacity for organic dyes in water [173]. Wang et al. employed alumina (Al_2O_3) as a nanosorbent and investigated the sorption mechanism of europium ion (Eu(III)) under varying pH levels, humic acid (HA) concentrations, and ionic strengths [174].

Magnetic metallic Ni nanoparticles offer promising capabilities for dye adsorption. The removal of dyes from wastewater is essential, as organic dyes constitute significant pollutants in water bodies, compromising water quality and posing risks to human health due to their toxicity, mutagenicity, and carcinogenicity. Jin et al. validated the effectiveness of Ni nanoparticle composites in isolating dyes from aqueous solutions. Their research indicated that Ni nanocomposites, characterized by large pore volumes and high surface areas, can be conveniently separated from the aqueous solution using an external magnet [175]. Ghaedi et al. introduced Ni sulfide nanoparticles supported on activated carbon as an innovative adsorbent for the individual and simultaneous adsorption of methylene blue and safranin-O [176]. Sudhasree et al. detailed the production of surfactant-free Ni nanoparticles, which were then applied to remove Congo red, an azo dye commonly found in industrial wastewater [177]. Zhang and colleagues validated the production of Ni nanoparticles, characterized by exceptional magnetic properties and a crystallite size ranging from 10 to 30 nm. These synthesized Ni nanoparticles were then employed as effective adsorbents for Congo red removal from industrial wastewater [178].

3.2. Carbon-Based Nanomaterials

Carbon-based nanomaterials encompass a diverse range of structures, including CNTs, graphene/graphene oxide sheets, fullerene, etc. (Figure 4) In recent years, carbon-based nanomaterials have emerged as promising candidates for addressing the challenges associated with wastewater treatment due to their exceptional properties, including a large surface area, high chemical stability, and highly tunable surface chemistry.

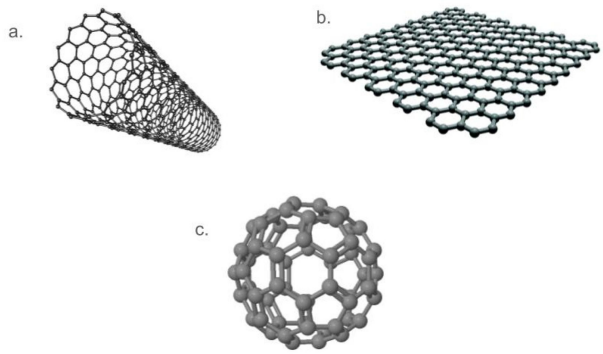


Figure 4. Three-dimensional structures of (**a**) carbon nanotubes, (**b**) graphene sheets, and (**c**) fullerene. Figure is obtained from [179] and reused under a Creative Commons license.

3.2.1. Carbon Nanotubes

Carbon nanotubes are one of the allotropes of carbon, first identified at least 30 years ago. They are among the strongest, lightest, and most hydrophobic materials available [180]. Carbon nanotubes are created by rolling graphene sheets into cylindrical tube shapes. If a single layer of graphene is rolled, it forms a single-walled carbon nanotube, whereas multiple layers of graphene rolled together result in multi-walled carbon nanotubes. The different synthesis methods used include laser ablation, arc discharge, electrophoretic deposition, and chemical vapor deposition [181,182].

CNTs are considered standard materials for the purification of water. A significant quantity of carbon nanotubes is employed to capture water pollutants present in large amounts. CNTs are very efficient in eliminating heavy metals from water bodies. Various measures were taken by many researchers towards the functionalization and purification of carbon nanotubes [183].

Mesopores and chemical stability set CNTs apart from more conventional adsorbents including clay, zeolites, metal oxides, activated carbon, and polymers. CNTs are distinct due to their special mechanical, chemical, electrical, and thermal characteristics. They can purge aqueous solutions of a variety of contaminants [184]. CNTs are highly preferred due to their exclusive properties, including their disinfection capacity, antifouling properties, strength, and permeability. CNT membranes can surpass the performance of reverse osmosis, nanofiltration, ultrafiltration, forward osmosis, and microfiltration. Additionally, they offer a slight reduction in cost due to the hydrophobic hollow nature of CNTs, requiring minimal external energy to propel water molecules through them [185].

Gunawan et al. [186] developed a hollow fiber membrane made of polyacrylonitrile which was then coated with a composite comprising silver and multi-walled carbon nanotubes. This innovative composite layer significantly inhibited the formation of biofilm on the membrane surface and effectively prevented bacterial growth within the filtration module. Polymer metal-organic CNT composites have shown promise in removing heavy metals. In a recent study aimed at removing arsenic from water, two adsorbents, Zn-BDC@chitosan/CNT and Zn-BDC@Chitosan/graphene oxide, were investigated. The study revealed that the composite of graphene oxide with the metal-organic framework and chitosan outperformed its CNT counterpart. This superiority was attributed to the higher specific surface area and the presence of active sites in graphene oxide [187].

Ahmed et al. [188] conducted a study utilizing a nanocomposite consisting of poly-N-vinylcarbazole and single-walled CNTs. The findings indicated that this nanocomposite resulted in the inactivation of over 80% of microbial cells. Numerous studies conducted by various researchers have demonstrated that chemisorption plays a predominant role in enabling CNTs to remove a wide range of pollutants. Additionally, it has been established that the adsorption process can be effectively modeled using pseudo-second-order kinetics. The adsorption capacity of the CNT is highly influenced by the pH value. To increase their chemical and mechanical strength, CNTs are grafted on polymers [189].

3.2.2. Fullerenes

Fullerene is another significant carbon-based material that holds a crucial position in water and wastewater treatment processes. Fullerenes are synthesized by a very slow condensation method of carbon in the vaporized phase [190].

Fullerenes such as C60 and C70, along with their derivatives, are recognized for their disinfection properties [191,192]. Typically, carbon vapor condensation proceeds slowly, leading to the formation of spherical fullerenes. Nonetheless, the introduction of a catalyst during the synthesis process can induce the formation of tubular or ring-like structures. Fullerenes are commonly denoted as C20 + n, and the spherical family, particularly C60, has garnered significant attention due to its distinctive sp2 hybridization and remarkable mechanical resilience [193].

Enhancing the solubility of nC60 requires functionalization, a process acquired through the utilization of carbon nanotubes. Introducing carboxyl, hydroxyl, and epoxy groups, and heteroatoms, enhances the material's ability to bind organic molecules in an aqueous environment via covalent or non-covalent interactions. These properties render C60 suitable for various environmental applications. Studies have indicated that under certain conditions, C60 exhibits no cytotoxicity or harmful effects and has a neutral biological impact [194–196].

Adam et al. reported a magnetic fullerene nanoparticle prepared by the combination of fullerene CNT and $ZnFe_2O_4$. This nanomaterial was used for the removal of Hg (II),

Cd(II), Sn(II), and Pb(II). The adsorption ability of fullerene is increased by adding $ZnFe_2O_4$ by at least 25%, and it also improves the reusability of the adsorbent [197].

3.2.3. Graphene-Based Nanomaterials

Graphene can be described as an organized honeycomb-like network of graphite. Modified forms of graphene like its oxides and reduced oxides can be further treated as adsorbents. Various functional groups, including carbonyl, epoxy, and hydroxyl groups, are employed to modify graphenes [198]. Graphite is taken as the raw material for the fabrication of graphene. Graphene with a single layer has good flexibility, high resistance, and high electrical and thermal conductivities that make it a popular choice for different applications. Exfoliation is a commonly employed method for the mass production of graphene; however, its application does not assure purity [199].

Studies have reported that graphene oxide and reduced graphene oxide can efficiently eliminate effluents such as metallic ions and organic wastes. Graphene-based nanomaterials exhibit excellent adsorption capacity in comparison to activated carbon, CNTs, and resins [199].

Graphene oxide (GO) bound with EDTA has shown remarkable effectiveness as an adsorbent. EDTA-GO exhibits excellent performance in removing hazardous heavy metals like Pb(II), Cu(II), Ni(II), and Cd(II) from aqueous solutions. In comparison to carbon nanotubes, the adsorption capacity of EDTA-GO for Pb (II) was determined to be four–five times greater, and one–two times greater than that of GO alone. The optimum pH for enhanced adsorption was seen at around 6.5–7. The Langmuir adsorption model was found to be consistent with the experimental data [200].

Yang et al. studied the adsorption capability of polar and non-polar substances by colloidal GO [201]. They discovered that GO has a substantial affinity for every substance they examined. Reduced graphene oxide (rGO) showed a superior adsorption capacity for non-polar aromatic organic molecules such as PAHs and nitroaromatic compounds compared to graphene oxide. This demonstrates how crucial it is to characterize wastewater before applying the best nanomaterial for treatment. GO can reduce the adsorption because of its surface oxidative debris, which can lower the adsorption performance.

3.2.4. Other Carbon-Based Nanomaterials

In recent studies, covalent graphitic carbon nitride (g-C_3N_4) has emerged as a highly promising semiconductor, particularly notable for its potential as a photocatalyst. This material stands out due to its unique tri-s-triazine ring structure and remarkable degree of condensation, which contributes to its exceptional thermal and chemical stability. g-C_3N_4 nanoparticles are often used for the removal of dyes from water and wastewater using photocatalytic degradation methods. In photocatalytic reactions, semiconductor catalysts facilitate either oxidation or reduction processes. When these catalysts are illuminated, they generate electrons (e−) and holes (h+). The OH* radical serves as the primary oxidant in the photodegradation of carbon-based pollutants, alongside other active species like h+ and the O_2*− radical. The electron transfer from the valence band to the conduction band leads to the formation of holes (h+) in the valence band [202]. Without electron-hole scavengers, photogenerated electrons recombine with holes, leading to a reduction in photocatalytic efficiency. Scavenging species enhance the efficiency of the photocatalytic reaction by inhibiting charge carrier recombination [203].

Carbon nitride nanocomposites effectively degrade dyestuffs present in wastewater. Heterojunction semiconductor-based g-C_3N_4 nanocomposites are particularly employed for the efficient removal of dyes, notably azo dyes like Rhodamine B, Methylene Blue, and Methyl Orange, from both water and wastewater. Pristine g-C_3N_4 demonstrates the photodegradation of Rhodamine B, methylene blue, and Methyl Orange in the order of RhB > MB > MO [202].

Li et al. [204] combined Bi_2O_3/g-C_3N_4 for the photodegradation of Rhodamine B under visible light irradiation. The degradation process followed pseudo-first-order kinetics.

Among the composites tested, Bi_2O_3/(53.2%) g-C_3N_4 exhibited the highest performance, displaying reaction rates 3.2 and 4.0 times faster than those of pure g-C_3N_4 and Bi_2O_3, respectively. $GdVO_4$/g-C_3N_4 was synthesized through a milling and heating method devised by He et al. [205]. Chen and Zang formulated an In_2O_3/g-C_3N_4 photocatalyst, which achieved a complete degradation of Rhodamine B within 60 min under visible light irradiation [206].

3.3. Hybrid Nanocomposites

A nanocomposite is a solid material consisting of multiple phases, each with dimensions under 100 nm. This substance can restrict the release of the nanoparticles in water produced to mitigate negative effects and boost the efficacy and efficiency of nanomaterials. One effective approach for tackling technical challenges involves synthesizing hybrid nanocomposites by depositing fine particles onto solid particles of a larger size. This method has proven effective in various applications, including wastewater treatment and gas separation [207]. A variety of nanocomposites can be fabricated by altering the composition, such as surfactants, nanofillers, mobile materials, or polymers [208]. Many nanocomposites display excellent performance in water treatment, environmental protection, and reusability, and are very cost-effective [209,210].

3.3.1. Metal/Metal Oxide-Based Nanocomposites

Due to the often low mechanical strength of nano metal oxides, they are commonly supported or impregnated by larger-sized porous materials, such as nano materials like zeolites or CNTs, to produce nanocomposites that are more practical and versatile [211]. ZnO is a semiconductor photocatalyst capable of generating electron-hole pairs under UV light exposure. Its characteristics comprise photostability, a low operational temperature, chemical stability, insolubility in water, and non-toxicity, rendering it highly effective for photocatalytic activities. As a result, ZnO is widely employed for numerous applications [212,213]. However, when exposed to visible light, its large band gap (3.2 eV) reduces its performance. Various approaches have been employed, such as conjugating with other semiconductor materials or doping with nonmetals/transition metal ions, to broaden the band gap and hinder the recombination of photogenerated electron-hole pairs, thereby enhancing the photocatalytic activity of ZnO [213].

Chen and colleagues demonstrated the synthesis of a ZnO/Bi_2WO6-CC composite through thermal decomposition, showcasing its efficacy in the photodegradation of MB. Their findings revealed a remarkable degradation rate, with approximately 96% of MB decomposed after 100 min of exposure [214]. Ebrahimi et al. demonstrated the photocatalytic degradation of 66.2% of 2,4-D by utilizing a Mn-doped zinc oxide/graphene nanocomposite under LED radiation for 120 min [215]. Likewise, Zhu and colleagues illustrated the degradation of RhB dye using a CuO-CuS-ZnO-ZnS nanocomposite, achieving the elimination of over 90% of the RhB dye under simulated sunlight [216].

Saleh and Gupta produced a nanocomposite comprising carbon nanotube/tungsten oxide and examined its catalytic efficacy for eliminating rhodamine B from wastewater under sunlight exposure [217]. Conventional porous materials have certain drawbacks, such as a limited adsorption capacity, difficulty in regeneration, specificity, selectivity, etc. To overcome the drawbacks of conventional porous material in wastewater treatment, several studies were conducted on the usage of metal-organic frameworks incorporating carbon nanotubes (MOF/CNTs) as a potable material [218,219]. Research indicates that incorporating CNTs into metal-organic frameworks (MOFs) can enhance the adsorptive elimination of dye pollutants from wastewater streams [219].

A Cu-BTC/CNT hybrid nanocomposite adsorbent was synthesized and examined for its efficacy in removing methylene blue (MB) from aqueous solutions. Han et al. developed a CNT/MIL-68(Al) composite that works efficiently for the removal of phenol contaminants from water [220]. Zinatloo-Ajabshir and colleagues synthesized a $Dy_2Sn_2O_7$-SnO_2 nanocomposite for the removal of organic contaminants utilizing a photocatalytic mechanism [221].

3.3.2. Polymer-Based Nanocomposites for Water Treatment

Polymer-based nanocomposites are considered the most eco-friendly and show high performance values, hence gaining much attention worldwide. Natural biodegradable polymers are suitable candidates for the matrix components in nanocomposites. They include proteins, lipids, and polysaccharides [222]. Polymeric membranes are prevalent in various applications because of their high selectivity, diverse membrane structures and properties, ease of fabrication, and controllable pore formation, and the cost-effectiveness of polymers [223]. The synthesis of thin film nanocomposite membranes and nanocomposite membranes has mainly been performed using two methods. The first method is to deposit elements at the designed nanoscale onto the surfaces of polymeric membranes. The second strategy uses a simple framework of tailored nanoscale components inside a polymeric matrix to synthesize mixed matrix nanocomposite membranes [30]. Mapthua et al. developed a membrane composed of a carbon nanotube–polymer composite, incorporating a polyvinyl alcohol barrier layer, to facilitate the separation of oil from wastewater [224].

Nanoscale pores are present in various nanocomposite membranes employed in water treatment to achieve selectivity. To achieve high selectivity in the porous membrane through the size exclusion mechanism, a pore size typically smaller than 1 nm is commonly employed [225–227]. Recently, Zhao and collaborators introduced a novel approach involving polyphenol-metal-influenced nano-hybridization to fabricate carbon nanotube membranes with anti-oil-fouling properties. These membranes were designed to achieve an excellent flux, antifouling characteristics, and self-cleaning oil/water separation [228].

Ebert et al. discovered that incorporating TiO_2 inorganic particles into polyvinylidene difluoride and poly(amide-imide) membranes enhanced their resistance to temperature and permeability [229]. Haider and colleagues [230] demonstrated the immobilization of silver nanoparticles onto polyethersulfone membranes by introducing amino groups, resulting in aminated polyethersulfone (APES). The antibacterial efficacy was evaluated against *Escherichia coli*. Singh et al. studied how guar gum fabricated with poly (methyl methacrylate) can be utilized for water purification along with Cr (VI) [231]. Mak et al. employed polyacrylic acid (PAA)-bound iron oxide magnetic NPs for the efficient removal of methylene blue (MB) from aqueous solutions [232].

3.4. Miscellaneous

Several studies have proved that boron nitride can be used for inorganic and organic contaminants' adsorption. Boron nitride has some unique properties, like high porosity, durability, and resistance towards oxidation that prove it a good agent for wastewater treatment [233–235]. This study compared the photocatalytic degradation of perfluorooctanoic acid (PFOA) in water using boron nitride (BN) and anatase TiO_2 under acidic and neutral pH conditions. BN exhibited significantly faster PFOA degradation rates than TiO_2 in both pH environments. This superior performance of BN was attributed to its higher surface hydrophobicity, which facilitated an increased PFOA surface coverage and more favorable interactions with photogenerated holes. These findings emphasize the importance of surface hydrophobicity in photocatalysis and suggest potential design strategies for enhancing the degradation of persistent surfactants like PFOA [236].

Extensive research by Davis et al. [237] has been conducted on the use of algal biochar as a bio-sorbent to eliminate toxic dyes and heavy metals. Liu et al. developed titanate nanotubes in a hydrothermal method that can effectively eliminate toxic thallium ions. The adsorption equilibrium is reached within 10 min, and the adsorption process occurs rapidly [238]. Cobalt nanoparticles combined with magnetic mesoporous carbon (Co/OMC) are being developed by Tang and his team for Rhodamine B(RhB)'s efficient adsorption [239]. Liu and co-workers utilized porous hollow silica nanoparticles (PHSNs) to remove the water-soluble pesticide validamycin. PHSNs offer numerous active sites for adsorbing validamycin, including the external surface, interspace of the surface, and the pore channels within the shell or internal core of PHSNs [240].

4. Challenges and Future Scope

Nanomaterials have emerged as promising candidates for wastewater treatment due to their unique properties and high efficacy in pollutant removal [241,242]. However, the widespread implementation of nanomaterial-based treatment technologies faces significant challenges across various fronts. One of the primary challenges in the utilization of nanomaterials for wastewater treatment is the associated cost. Many nanomaterials are expensive to produce or acquire, which limits their adoption, particularly in regions with limited resources. To address this challenge, research efforts should focus on exploring cost-effective synthesis techniques and scalable production processes. By enhancing the economic viability of nanomaterial-based treatment technologies, their widespread adoption can be facilitated, thereby improving water quality and accessibility. Furthermore, concerns regarding the potential environmental release of nanomaterials during wastewater treatment operations pose another significant challenge. To mitigate this risk, it is imperative to gain a thorough understanding of the behavior, fate, and long-term implications of nanoparticles in receiving water bodies. Robust monitoring systems and risk assessment protocols should be established to ensure the safe utilization and disposal of nanomaterials, minimizing any adverse ecological consequences.

Certain nanomaterials may undergo transformations or degradation under specific conditions, affecting their efficacy and longevity in wastewater treatment applications. To address this challenge, research should focus on enhancing the stability and resilience of nanomaterial-based treatment systems across diverse operating conditions. This may involve the development of novel nanocomposites or surface modifications that improve the durability of nanomaterials in harsh wastewater environments.

Despite promising results at the laboratory scale, transitioning nanomaterial-based treatment technologies to larger-scale systems presents significant challenges. Issues such as aggregation, fouling, and engineering complexities need to be addressed to successfully scale up these technologies for practical applications [243]. Collaborative research efforts between academia and the industry are essential in overcoming these challenges and facilitating the widespread adoption of nanomaterial-based treatment technologies.

While nanomaterials often possess high adsorption capacities, their ability to selectively target specific contaminants in complex wastewater streams may be limited. To optimize wastewater treatment efficiency, research should focus on developing nanomaterials with enhanced selectivity towards target pollutants, while minimizing interference from other substances. This may involve the design of functionalized nanomaterials or the integration of nanocomposites with selective adsorption properties.

Certain nanomaterials may pose risks to human health and the environment due to their toxicity or bioaccumulative properties. Therefore, it is essential to conduct comprehensive assessments to understand the potential health and environmental impacts of nanomaterial exposure. Risk assessment strategies should be developed to ensure the safety of nanomaterial-based treatment technologies, thereby minimizing any potential adverse effects on human health and the environment.

5. Conclusions

The utilization of nanomaterials holds significant promise for revolutionizing wastewater treatment and addressing global water challenges. In conclusion, this review emphasizes the advancements made in utilizing nanomaterials for wastewater treatment, with a specific focus on iron oxide, nanosilver, TiO_2, ZnO, and CuO, as well as other nanoparticles. Furthermore, carbon-based nanomaterials, such as nanotubes, graphene-based nanosheets, fullerenes, and their nanocomposites, were also discussed in this regard. Additionally, diverse nanotechnology-based water treatment techniques were addressed for the removal of water pollutants.

With their unique properties and high efficacy in pollutant removal, nanomaterials offer innovative solutions that can enhance the efficiency and sustainability of wastewater treatment processes. By leveraging the remarkable characteristics of nanomaterials, such

as a high surface area, enhanced reactivity, and tunable properties, advanced treatment technologies can be developed that are capable of efficiently removing contaminants from wastewater streams. Furthermore, nanomaterial-based treatment approaches can overcome many limitations associated with conventional methods. However, their large-scale production often faces many hurdles. Addressing these challenges and harnessing the transformative potential of nanotechnology can lead to the development of more efficient, cost-effective, and environmentally sustainable wastewater treatment solutions. Continued research, collaboration, and innovation in this field are essential for fully realizing the benefits of nanomaterials in tackling global water challenges and ensuring access to clean and safe water resources for all.

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