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Review

Recent Advances in Nanomaterial-Based Wastewater Treatment: A Sustainable Approach

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Abstract

Water scarcity and the demand for potable water are affecting people globally, particularly in developing nations with growing populations. Annually, numerous contaminants such as dyes, heavy metals, pesticides, microorganisms, and hydrocarbons adversely affect aquatic life and ecosystems, rendering the water unfit for human consumption. Innovations in water treatment technology have emerged to address the scarcity of accessible water and the rising levels of contamination. Adsorption is crucial for environmental restoration and has attracted significant attention in both scientific research and industrial applications. The field of environmental nanotechnology has advanced rapidly in recent years, driven by the swift growth of nanotechnology and the development of nanomaterials. Nanoscale materials are attracting considerable attention in worldwide development efforts because of their distinctive characteristics. Their nanoscale dimensions have led to improved catalysis, heightened receptivity, and augmented adsorption capabilities. Metal oxide nanoparticles like titanium dioxide (TiO_2), zinc oxide (ZnO), and iron oxide (Fe_3O_4) exhibit remarkable adsorption capabilities, rendering them particularly efficient in the elimination of heavy metals, organic pollutants, and microbial contaminants from water. The application of nanotechnology in wastewater management represents a significant commitment to enhancing the efficiency and effectiveness of water purification, offering a sustainable approach to protecting water resources. This review examines the fundamental concepts and stages of the absorption process, along with the most recent findings on nanomaterials, including carbonaceous nanomaterials, metal-containing nanoparticles, and nanocomposites.

Keywords: humanity, environmental nanotechnology, adsorption capacity, elevated reactivity

Introduction

Water contamination presents an escalating environmental issue on a global scale. Elements including industrial expansion, increasing population, and climate variations play a crucial role in the contamination of vital water bodies such as rivers and lakes. The World Health Organization (WHO) has emphasized the significant health hazards linked to polluted water and insufficient sanitation, impacting millions of individuals worldwide annually. At present, almost two billion people live in areas facing water scarcity, a challenge anticipated to intensify as a result of climate change and increasing population pressures [1].

A diverse array of pollutants, such as dyes, heavy metals, pesticides, hydrocarbons, and microbial

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contaminants, leads to the contamination of freshwater, rendering it unsafe for consumption. Heavy metals like mercury, arsenic, copper, nickel, and zinc represent a considerable risk to aquatic ecosystems and human health. Studies indicate that contact with specific heavy metals, such as zinc and mercury, may cause alterations in protein structure, which could lead to significant health issues, including cancer [2, 3].

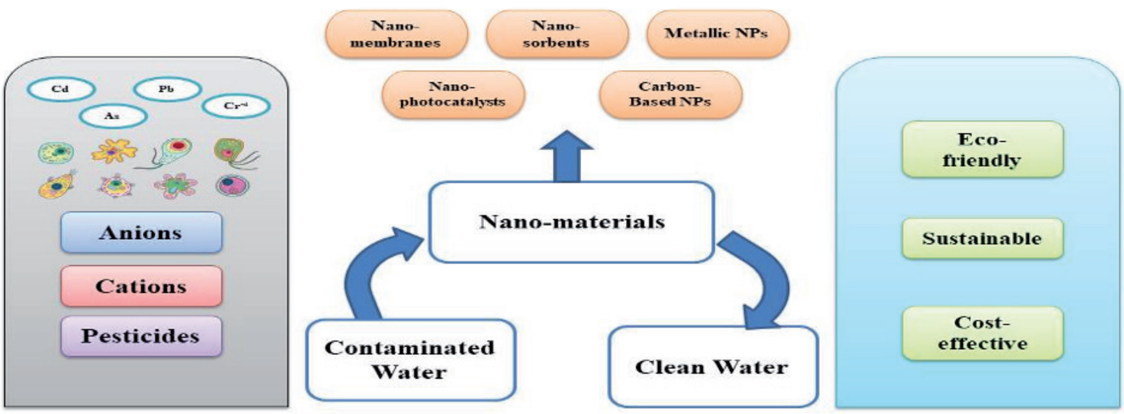
In recent years, there have been notable advancements in wastewater treatment methods, emphasizing a range of techniques including electrocoagulation (EC), photocatalysis, advanced oxidation processes (AOPs), adsorption, and membrane filtration. Furthermore, techniques for wastewater management utilizing nanotechnology have attracted significant interest owing to their effectiveness in eliminating pollutants. Nanomaterials, such as carbon nanotubes, metal nanoparticles, and bio-based adsorbents, demonstrate superior adsorption capabilities, rendering them particularly efficient in the removal of contaminants from water. Research has indicated the application of chitosan-coated gasifier biochar for the extraction of cadmium (Cd^{2+}) and copper (Cu^{2+}) from water solutions [4].

Recent years have seen growing concerns regarding emerging contaminants, particularly pharmaceuticals and personal care products. The presence of pollutants such as antibiotics, hormones, and cosmetic residues in water bodies is on the rise, raising concerns about potential risks to human and environmental health. Traditional water treatment methods frequently do not adequately eliminate these pollutants, highlighting the need for the implementation of more sophisticated purification approaches [5, 6].

Guaranteeing access to clean drinking water is an essential global concern, and investigators are persistently examining economical and sustainable methods to improve water quality [7]. The fundamental processes in wastewater treatment encompass primary, secondary, tertiary, and pre-treatment stages [8]. Every phase fulfills a specific role, ranging from the extraction of larger debris and suspended particles to the eradication of microbial contaminants, pharmaceutical residues, and dissolved solids. Methods like sequencing batch reactors (SBRs) and coagulation techniques are frequently employed in secondary treatment to improve the efficiency of water purification. Advanced treatment processes effectively remove pathogens, odors, and surplus nutrients to guarantee the safety of water [9, 10].

While conventional water treatment techniques have proven effective, the presence of new contaminants necessitates the development of innovative and flexible technologies to ensure lasting water sustainability. A particularly promising method involves the application of nanotechnology in the treatment of wastewater [11, 12]. Nanomaterials significantly improve filtration and adsorption processes, providing an efficient approach for eliminating various pollutants, such as heavy metals, organic contaminants, and harmful microorganisms. Thanks to their distinct characteristics – including an extensive surface area, elevated reactivity, and adjustable hydrophilic or hydrophobic qualities – nanoparticles demonstrate exceptional efficacy in water purification. Research has shown that different nanomaterials can successfully remove harmful metals such as lead (Pb) and molybdenum (Mo), while also tackling the growing concern of new contaminants [13-15].

Advancements in nanotechnology indicate a significant potential for improving wastewater treatment, leading to cleaner and safer water supplies in the future. Ongoing exploration and innovation in this area will be essential for securing enduring water management solutions for future generations. Significant advancements have been achieved in the application of metal and metal oxide nanoparticles, as well as carbon-based nanomaterials like nanotubes, graphene-based nanosheets, fullerenes, and their composites, for wastewater treatment purposes. The present evaluation thoroughly investigates all of these advancements,



Scheme 1. Treatment of wastewater containing impurities like heavy metals, pesticides, anions, cations, etc., with nanomaterials such as nanomembranes, nanosorbents, etc., to obtain clean and pure water.

analyses various nanotechnology-driven water treatment techniques, and encompasses the latest progress in water treatment systems employing an extensive array of nanomaterials.

Varied Approaches to Water Treatment

Effective wastewater treatment is essential for sustainable water management, utilizing a combination of physical, chemical, and biological techniques to eliminate contaminants. Fig. 1 illustrates the various strategies for treating wastewater through physical, chemical, and biological methods.

Various methods, including physical, chemical, and biological approaches, are extensively employed for the treatment of wastewater, with each presenting distinct benefits and uses: Physical techniques encompass screening, sedimentation, filtration, and membrane technologies. These processes eliminate insoluble particles and impurities from effluents [16]. Innovative physical methods such as ultrasound irradiation and nanoparticle treatment have demonstrated potential in water purification by producing reactive oxygen species capable of disrupting bacterial cells [17]. Dissolved air flotation, coagulation-flocculation, and electrocoagulation represent effective physical treatment methods; however, they often necessitate substantial space and considerable financial investment [18]. Chemical techniques frequently encompass processes such as coagulation, flocculation, and disinfection. The application of ozonation has demonstrated an improvement in the coagulation-flocculation process for treating textile wastewater, resulting in notable decreases in COD and turbidity levels [19]. Innovative chemical treatments such as advanced oxidation processes and electro-Fenton techniques are gaining recognition for their ability to effectively break down persistent pollutants. Biological approaches employ microorganisms to decompose organic material and eliminate nutrients. This encompasses aerobic methods such as activated sludge and trickling filters, along with anaerobic digestion [20]. Membrane bioreactors integrate biological treatment with membrane filtration, providing effective pollutant removal while encountering issues related to membrane fouling. Anaerobic membrane bioreactors demonstrate potential for effectively managing intricate pharmaceutical waste and simultaneously recovering energy [21]. Integrated strategies that combine physical, chemical, and biological methods have garnered interest for their ability to address the shortcomings of standalone treatments. These hybrid systems have the potential to enhance efficiency, lower energy usage, and support the principles of a circular economy. The integration of ozonation, physical-chemical treatment, and nanofiltration has demonstrated remarkable effectiveness in the treatment of textile wastewater. In summary, although every method presents its own advantages and drawbacks, the direction is leaning towards cohesive strategies that merge various treatment techniques. These hybrid systems enhance performance and reliability in addressing various wastewater streams, particularly those containing emerging pollutants such as pharmaceuticals and personal care items. The selection of a treatment approach is influenced by the unique characteristics of the wastewater, the quality of the effluent sought, and financial factors.

The methods employed for water purification, such as oxidation, reverse osmosis, deionization, and demineralization, frequently face limitations due to the introduction of harmful pollutants into the environment.

In water treatment, oxidation processes play a crucial role as they offer various applications throughout the treatment process. These approaches tackle a range of issues related to water quality through their application in pre-oxidation, intermediate

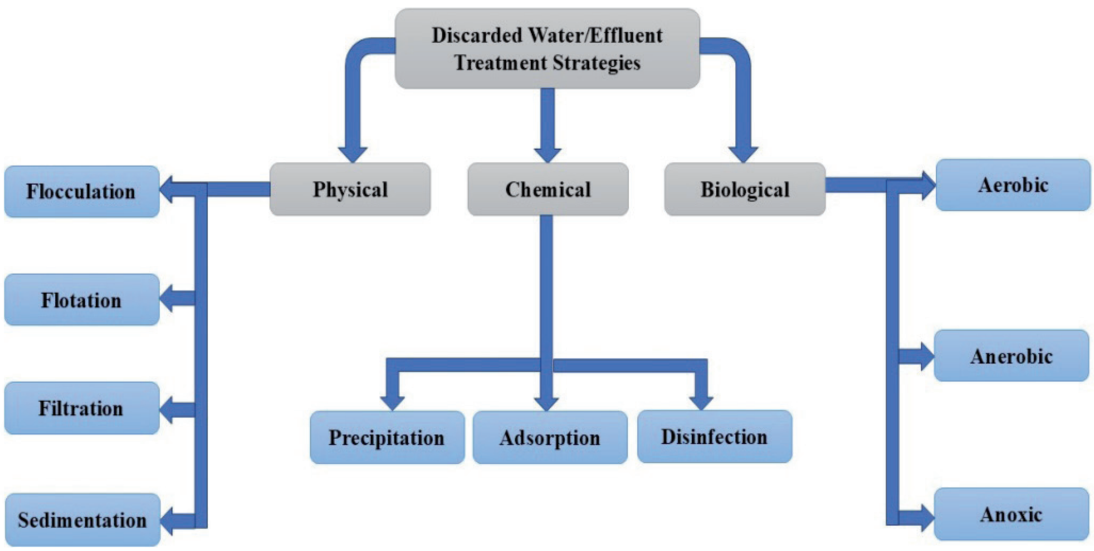


Fig. 1. Wastewater treatment strategies [22].

oxidation, and final disinfection processes. Ozone has been employed for the treatment of drinking water since 1906, initially for disinfection purposes, and now also for flocculation, oxidation of both organic and inorganic pollutants, as well as the enhancement of aerobic biological processes [23].

It is noteworthy that oxidation techniques can effectively eliminate various pollutants; however, they may also generate potentially harmful byproducts. For instance, Rigobello and colleagues indicated that diclofenac (DCF) experienced partial removal when subjected to oxidation with chlorine and chlorine dioxide, although this process produced byproducts; chlorine dioxide demonstrated greater efficacy compared to chlorine [24]. Similarly, iodide can generate iodinated aromatic compounds that exhibit heightened toxicity, persistence, and bioaccumulation through periodate-based oxidation [25].

In a similar vein, reverse osmosis (RO) serves as a prevalent method for water treatment, yielding high-quality water suitable for drinking supply and desalination [26]. Nonetheless, membrane fouling presents a significant challenge, as it diminishes operational flow, reduces water output, and increases power consumption in reverse osmosis systems. The challenge of addressing fresh water sources is prevalent and necessitates extensive and expensive pre-treatment processes. Furthermore, due to the presence of inorganic elements such as silica, calcium, iron, and phosphate, reverse osmosis systems encounter challenges when dealing with water that has elevated salinity levels and are susceptible to scaling issues [27, 28].

As a result, due to advantages such as reduced energy usage and environmental sustainability, capacitive deionization (CDI) is increasingly recognized as a promising method for water treatment and desalination [29]. The efficiencies for hardness and conductivity removal in CDI systems reach a minimum of 70.8% and 51.9%, respectively. These systems demonstrate the ability to eliminate ions from diverse water sources, such as brackish water, tap water, and industrial effluent [30]. A fascinating paradox emerges in the management of mixed pollutants. Some studies indicate that CDI can effectively eliminate inorganic salts along with trace organic contaminants [31], while others emphasize the difficulties presented by the presence of organic pollutants in real wastewater scenarios [32]. This variation indicates that the efficacy of CDI could differ based on the particular makeup of the wastewater undergoing treatment.

The constraints of current methods and the increasing environmental challenges have prompted the exploration of more sustainable approaches to water treatment.

Magnetic Separation Techniques

The application of nanomaterials in magnetic separation has proven to be a highly effective method for treating wastewater. Iron oxide nanoparticles, especially magnetite (Fe_3O_4), are extensively utilized because of their distinctive characteristics, including affordability, elevated surface area, and significant adsorption capacity. The separation of these nanoparticles from treated water is facilitated by external magnetic fields, resulting in an efficient and uncomplicated process [33, 34].

The procedure generally encompasses these stages: Initially, magnetic nanoparticles undergo functionalization or modification to improve their ability to adsorb particular pollutants. Subsequently, these nanoparticles are incorporated into the wastewater, facilitating the adsorption of the specific contaminants. Ultimately, an external magnetic field is utilized to segregate the nanoparticles along with the attached pollutants from the processed water. Notably, the effectiveness of magnetic separation can be enhanced through the development of tailored separation units. A magnetic separation unit incorporating a zigzag pathway design has been created to enhance the capture of magnetic hydrogels, resulting in a separation efficiency exceeding 97%. Furthermore, the application of magnetic nanocomposites derived from clay minerals and magnetite has demonstrated an adsorption efficiency for anionic surfactants and polyphosphates that is 2-8 times greater than that of native clay minerals [35, 36].

Nonetheless, in spite of its efficacy, the application of magnetic separation with nanomaterials presents specific constraints. A notable challenge is the clustering of nanoparticles, which diminishes their ability to adsorb and separate effectively. This phenomenon arises from robust magnetic interactions between the particles, resulting in aggregation and a reduction in the active surface area. Furthermore, the enduring stability and reusability of magnetic nanoparticles present ongoing challenges, as they are susceptible to oxidation, dissolution, or surface alterations over time, which can impact their effectiveness. Another limitation is the possible emission of nanoparticles into the environment, which prompts concerns regarding ecological impact and toxicity. The inappropriate disposal or leakage of these nanoparticles may result in unforeseen contamination and impact aquatic ecosystems. Furthermore, the widespread adoption of this technology encounters financial obstacles, as the processes of synthesis, functionalization, and recovery of nanoparticles demand considerable investment and specialized knowledge. Ultimately, it is essential to refine external magnetic separation units to improve their separation efficiency and reduce energy consumption.

In summary, the application of magnetic separation with nanomaterials presents a compelling approach for wastewater treatment, characterized by its straightforwardness [37], effectiveness, and potential for reuse. Nonetheless, issues like the possible environmental effects of nanomaterials, the aggregation of nanoparticles, long-term stability, and the necessity for economically viable large-scale applications remain to be tackled [38]. Future investigations should concentrate on creating environmentally friendly synthesis techniques for magnetic nanomaterials and enhancing their regeneration abilities [39].

Membrane Filtration

Membrane filtration processes that utilize nanomaterials have surfaced as a compelling approach for wastewater treatment, delivering improved performance and efficiency relative to traditional methods [40, 41]. Nanomaterials, including nanoparticles, carbon nanotubes, graphene, and metal oxides, are being incorporated into membrane systems to enhance water permeability, mechanical strength, separation efficiency, and resistance to fouling. The integration of nanomaterials into membranes can be accomplished via two main approaches: incorporating nanoparticles into the polymeric matrix or applying them onto the membrane surface. These nanocomposite membranes demonstrate enhanced attributes, featuring improved hydrophilicity, porosity, and antimicrobial properties. For example, carbon nanomaterials such as fullerenes, graphenes, and CNTs demonstrate impressive adsorption rates and selectivity when addressing wastewater contaminants. It is noteworthy that, despite the considerable benefits presented by membranes enhanced with nanomaterials, there are also obstacles linked to their development and effects on the environment. The possible introduction of nanoparticles into the environment throughout the treatment process raises concerns that necessitate additional examination [42]. Nonetheless, the use of nanotechnology in membrane filtration has shown significant promise in tackling a range of water treatment issues, such as eliminating disinfection byproducts, toxic metal ions, organic pollutants, and microbial contaminants. In summary, membrane filtration processes that incorporate nanomaterials mark a notable progression in the technology of wastewater treatment. These advanced systems provide enhanced performance regarding contaminant elimination, resistance to fouling, and overall effectiveness. As investigations in this area advance, it is anticipated that membranes enhanced with nanomaterials will be pivotal in tackling worldwide water quality challenges and fostering sustainable practices in water management [43-45].

Catalytic Reduction

The catalytic reduction method employing nanomaterials demonstrates significant efficacy in addressing organic pollutants such as dyes and nitrophenols. It has developed into a promising approach for wastewater treatment, providing improved efficiency and effectiveness over conventional methods [11, 46]. The techniques mainly utilize nanocatalysts and nanoparticles to enhance the reduction of contaminants in wastewater. A significant application is the utilization of nano zero-valent iron (nZVI) for the catalytic reduction of diverse pollutants. nZVI has demonstrated impressive effectiveness in converting hazardous substances into less harmful compounds, especially in the remediation of heavy metals and organic contaminants. Furthermore, various nanomaterials, including titania, carbon nanotubes (CNTs), and silver nanoparticles, have shown catalytic properties that can improve water purification processes. Notably, the incorporation of nanomaterials into porous scaffolds or substrates has been shown to markedly enhance decontamination efficiency, featuring improved reaction kinetics and selectivity. The effect of nanoconfinement has been especially significant in iron-based nanomaterials, including various polymorphs of iron oxides, oxyhydroxides, and zero-valent iron. In summary, catalytic reduction methods utilizing nanotechnology present encouraging options for wastewater treatment, with nanomaterials such as nZVI, titania, and CNTs being integral components. The incorporation of these nanomaterials into diverse composites and their encapsulation within porous frameworks has demonstrated improved catalytic capabilities for water purification. Nonetheless, additional investigation is required to tackle issues concerning cost-effectiveness, environmental suitability, and the application of laboratory findings to extensive engineering practices [47-49].

Adsorption

Adsorption techniques are characterized as a surface phenomenon that entails the mechanical relationships between the adsorption material and the adsorbed surface, taking place without any chemical interaction. The process is known as physical adsorption. The focused presence of a particular component is noted at the surface or at the interface between the two states. The characteristics of chemical bonding, such as van der Waals forces, hydrophobicity, weak hydrogen bonds, pi-pi interactions, hydrogen bonds, and covalent and electrostatic interactions, play a crucial role in determining the effectiveness of the adsorption process between the pollutant and the adsorbent. The phenomenon of chemical adsorption occurs when chemical bonds play a role in the adsorption process. The surface of the adsorbent is the site where impurities are taken up across three distinct phases during the adsorption process. At the outset, the contaminants are moved from the adsorbent into the bulk solutions. Subsequently, the adsorption process occurs at the surface layer of the adsorbent, leading to the eventual transfer of pollutants into the adsorptive material. Additionally, various environmental factors such as pH, temperature, the nature of contaminants and adsorption materials, pollutant saturation levels, and the duration of interactions can influence the mechanisms involved in the absorption process [44-51].

Researchers view adsorption techniques as a comprehensive approach for removing both organic and inorganic pollutants from wastewater. The adsorption technique proves to be cost-effective for treating large volumes of wastewater due to lower costs related to equipment construction, upkeep, and operation. Moreover, the adsorption mechanism promotes the elimination of analytes rather than producing detrimental metabolites. The effectiveness of adsorption depends on the properties of the adsorbent used in the process. Although traditional substrates such as chelating agents, clay minerals, and activated carbon can remove heavy metal cations, their constrained sorption capacities may reduce their effectiveness in water treatment scenarios. The use of adsorbents with high sorption capacity could greatly improve the effectiveness of the treatment process. Recent advancements in nanotechnologies have enabled the use of nanoparticles for the detoxification of water. Materials with nanoparticle dimensions ranging from 1 nm to 100 nm demonstrate notable sorption properties. The application of contemporary nanotechnology in adsorption methods facilitates the creation of innovative nano adsorbents, which can be employed for the treatment of water or wastewater to remove pharmaceutical contaminants [52-54].

Varied Types of Nanomaterials

Nanomaterials can be engineered in laboratory settings by manipulating different variables to meet specific criteria. Additionally, NMs can emerge naturally as a result of different types of processes and activities in the environment. This will thoroughly analyze the classification of nanomaterials based on their shapes, origins, materials, and sizes [69].

Natural Nanomaterials

Natural NMs are substances generated through biogeochemical processes that take place in an unaltered environment, free from human intervention. The phrase "natural origins" pertains to these substances. Natural entities, including the capsids of viruses and bone compounds, possess these intrinsic substances. Numerous natural processes, such as those involving clay, contribute to the formation of these intrinsic substances [70]. Natural nanomaterials such as nano clay offer a cost-effective solution for wastewater remediation [71].

Engineered Nanomaterials

Substances created in a laboratory setting are known as laboratory-manufactured nanomaterials (NMs). The synthesis of these nanomaterials involves a variety of distinctive processes. The entities previously mentioned are organized into 3 primary categories, specifically:

1) Nanocomposites in the Treatment of Wastewater

Nanocomposites have surfaced as effective materials for wastewater treatment, showcasing distinctive properties and superior performance when compared to conventional methods. These materials combine the benefits of functional nanoparticles with different solid hosts, resulting in enhanced effectiveness in contaminant removal [72]. Nanocomposites that include nanoparticles, graphene, or its derivatives are commonly utilized in the treatment of wastewater. Nanocomposite membranes that include inorganic fillers such as carbon nanotubes, graphene oxide (GO), and metal nanoparticles have demonstrated enhanced hydrophilicity, resistance to fouling, and improved rejection efficiencies [73]. For example, nanocomposites infused with silver (Ag) nanoparticles demonstrate significant efficacy in wastewater treatment and exhibit strong antimicrobial characteristics. In a similar vein, iron-based magnetic nanocomposites have shown noteworthy effectiveness in the removal of pollutants, especially concerning toxic metals, pharmaceuticals, and pesticides. The integration of various nanofillers, including carbon nanotubes, graphene oxide, zinc oxide, titanium dioxide, and metal nanoparticles, into polymeric materials has resulted in notable progress in wastewater treatment. These nanocomposites effectively reduce pollutant buildup, enhance water affinity, boost performance, and strengthen mechanical characteristics [74, 75]. Furthermore, electrospun nanofibers, capable of being produced from a range of materials and enhanced with additional polymeric substances or nanomaterials, have demonstrated potential in the elimination of both organic and inorganic contaminants from wastewater [76]. In summary, nanocomposites present a variety of benefits for wastewater treatment, such as increased surface area, superior adsorption capacity, and heightened selectivity. Their capacity to efficiently eliminate various contaminants, including heavy metals and organic pollutants, positions them as a flexible approach to tackling water pollution issues [77]. Green nanocomposites sourced from biomass resources exhibit significant porosity, numerous active sites, and effective catalytic degradation properties for the treatment of dyes, heavy metals, and organic wastes [78]. Clay-based nanocomposites have garnered interest due to their distinctive physicochemical characteristics and economic advantages over traditional treatment approaches. These materials demonstrate enhanced surface area, thermal stability, and effectiveness in contaminant removal [79]. Nonetheless, although nanocomposites exhibit exceptional performance, their widespread use is affected by economic considerations, including elevated material synthesis and production expenses stemming from costly raw materials (like carbon nanotubes, GO, and metal nanoparticles) and energy-demanding processes. The requirement for specialized equipment and regulated environments significantly increases expenses. Furthermore, scalability continues to pose a challenge, necessitating sustainable synthesis approaches, such as bio-based production, to improve commercial feasibility. Operational expenses, including membrane fouling and maintenance, play a significant role in overall costs; however, advancements in self-cleaning and anti-fouling membranes could potentially lead to a decrease in long-term financial commitments. Furthermore, the need for compliance with environmental safety and disposal regulations necessitates additional investigation into biodegradable and recyclable nanocomposites to reduce related expenses while promoting sustainability [80, 81]. In summary, nanocomposite materials present potential solutions for tackling wastewater treatment issues; however, additional developments are required to enhance their economic viability and facilitate widespread implementation.

2) Nanomaterials Derived from Metals for Wastewater Treatment

Metal-based nanomaterials have shown significant promise in wastewater treatment due to their unique properties and high efficiency in removing various pollutants. These nanomaterials, including zero-valent metal nanoparticles (e.g., Ag, Fe, and Zn) and metal oxide nanoparticles (e.g., TiO_2, ZnO, and iron oxides), possess exceptional characteristics such as high surface-area-to-volume ratio, surface modifiability, excellent magnetic properties, and biocompatibility. These properties make them highly effective for removing heavy metals, organic pollutants, and microorganisms from wastewater [82].

Iron oxide nanomaterials, in particular, have received significant attention for their versatility as nanosorbents and photocatalysts. In a comparative study, iron oxide nanoparticles demonstrated a 75.9% chemical oxygen demand (COD) removal efficiency, slightly outperforming titanium oxide (TiO_2) at 75.5%. Iron nanoparticles achieved a 72.1% methyl blue removal efficiency, showcasing their effectiveness in treating organic pollutants [83]. Nanosized iron particles (nZVI) are highly reactive, cost-effective, environmentally friendly, and efficient in adsorption, making them ideal for water remediation. For instance, nZVI has been successfully evaluated for As(V) contamination removal at various pH values, with studies highlighting their superior surface modification, reactivity, magnetic properties, and biological compatibility. The outer layer of nZVI comprises iron oxides, while the inner layer is elemental iron (Fe [0]). Upon oxidation in water, the inner layer produces corrosion products such as lepidocrocite (α-, β-, and γ-FeOOH), goethite, and aragonite, all of which effectively adsorb pollutants [84, 85]. Nano-sized metal oxides, such as TiO_2 and ZnO, also play a crucial role in wastewater treatment. These materials efficiently remove endocrine-disrupting chemicals, cyanotoxins, antibiotics, and organic pollutants. For example, nano titanium oxide and copper oxide facilitate the electrocatalytic oxidation of organic molecules, significantly reducing chemical oxygen demand (COD). Studies have demonstrated their effectiveness in eliminating pesticides, dyes, polymers, phenolic compounds, aldrin, and polychlorinated biphenyls [86, 87]. Furthermore, nanoscale magnetic adsorbents have emerged as a major focus in recent nanoscience research. These materials have been extensively studied for their ability to remove toxic substances such as arsenic, cadmium, uranium, chromium, and phosphate toxins, as well as organic pollutants like dichlorophenol and methylene blue. Each nano-sized metal oxide exhibits unique mechanisms of action, enabling their application in diverse wastewater treatment scenarios. While metal-based nanomaterials offer numerous advantages, economic feasibility remains a challenge. Only a limited number of these materials have been commercialized for large-scale applications. Future research should prioritize the development of antimicrobial nanocomposites to enhance the stability and activity of metal and metal oxide nanoparticles in aqueous environments [39, 88]. These advancements could further optimize their performance and broaden their application in sustainable water treatment systems.

3) Nanomaterials Derived from Carbon for Wastewater Treatment

Because of possible non-toxic properties, structural qualities, quantity, porosity, large area of surface, with adequate sorption capabilities, various carbon-containing nanomaterials are increasingly being used in the present decades to remove heavy metals along with dyes. This is due to the fact that these nanomaterials possess all of these different characteristics [89]. Thus, carbon-based nanomaterials have emerged as promising agents for wastewater treatment due to their unique properties and versatile applications. These materials, including carbon nanotubes, graphene/GO, carbon dots, and fullerenes, exhibit exceptional adsorption capabilities and selectivity owing to their extensive surface area and customizable surface chemistry [90]. Their effectiveness in removing various pollutants from wastewater has been demonstrated in numerous studies.

Carbon-based precursors, the materials that serve the purpose in the manufacturing of activated carbon, including coal, wood, and coconut shells, are a kind of carbon that contains a dense pore with a large area of surface, and can be utilized as an absorbent in many applications. Agricultural wastes are also utilized in this process. Sawdust from coconut trees was used by Machado and his team in order to prepare activated carbon, which was subsequently utilized for the remediation of Cr (VI). An investigation on the phosphate impact in the forced hydrolysis of ferric chloride on improved granular activated carbon was carried out by Arcibar-Orozco and colleagues [91].

A comprehensive summary of various nanomaterials employed in wastewater treatment is presented in Table 1, emphasizing their distinct capabilities in pollutant removal. The performance of these nanomaterials is influenced by variations in surface area, modifications of functional groups, and their catalytic characteristics. For instance, TiO_2 and CNTs demonstrate exceptional adsorption capabilities owing to their elevated surface reactivity and proficiency in engaging with various contaminants. TiO_2 nanoparticles demonstrate

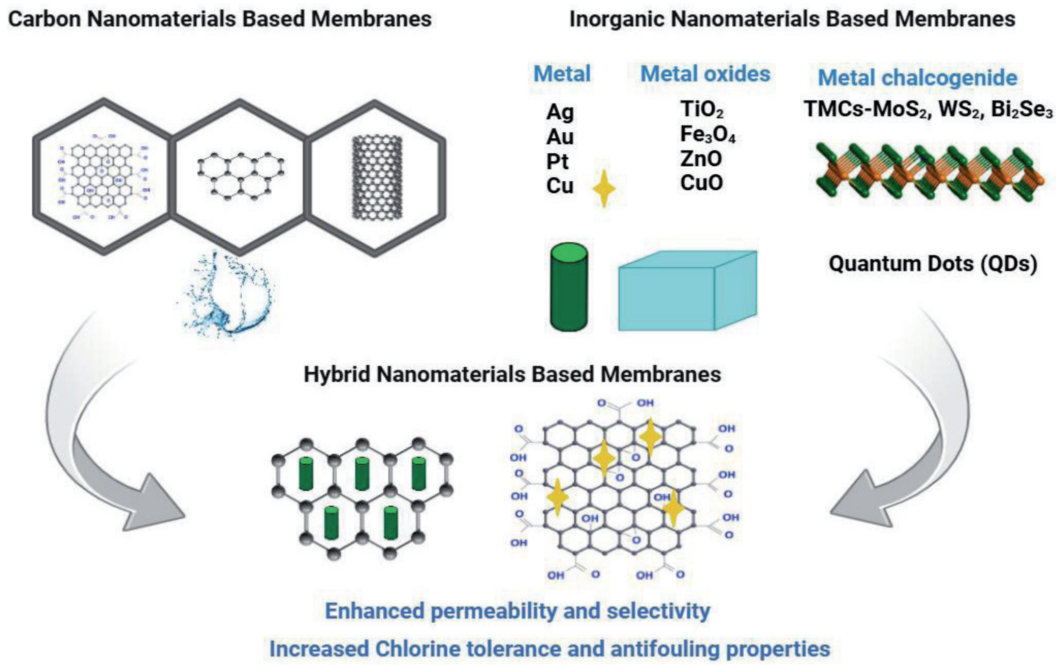


Fig. 2. Nanotechnology for remediation of wastewater [92].

significant efficacy in photocatalytic degradation through the generation of reactive oxygen species when exposed to UV light, facilitating the breakdown of organic pollutants. CNTs exhibit significant adsorption capabilities for heavy metals and organic dyes, attributed to their extensive surface area and π-π interactions. Magnetic nanoparticles, like Fe_3O_4, facilitate straightforward recovery through external magnetic fields, and their functionalized versions improve selective adsorption capabilities. Nonetheless, obstacles like aggregation, stability concerns, and the risk of metal ion leaching restrict their effective use. Graphene oxide (GO) and reduced Graphene oxide (rGO) exhibit significant capabilities for the adsorption of metals and emerging pollutants. While metal-organic frameworks (MOFs) demonstrate remarkable porosity and selectivity, the elevated costs associated with their synthesis continue to hinder widespread application.

Table 1. Applications of nanoparticles for the removal of water pollutants by adsorption.

Serial No.	Nanoparticle	Pollutant	Removal capacity (mg/g)	Reference
1	Chitosan	Methylene Blue Dye	43.4-423.5	[55]
2	Magnetic Chitosan	ALIzarin Red Dye	40.12-43.08	[56]
3	TiO_2	Red 195 Azo Dye	87	[57]
4	Magnetite	Methylene Blue Dye	70.4	[58]
5	Fe_3O_4	Orange G Dye	1883	[59]
6	MgO	F	21.1	[60]
7	SDS-coated Fe_3O_4	Cu (II), Ni (II), Zn (II)	24.3 - Cu (II)	[61]
8	Al_2O_3	Orange G	93.3	[62]
9	Halloysite nanotubes	Malachite green	99.6	[63]
10	Anatase	Pb (II), Cu (II), As (III)	31.25 - Pb (II)	[64]
11	Maghemite	Cr (VI)	19.20	[65]
12	Zero-valent Iron	As (III)	3.5	[66]
13	$MnFe_2O_4$	Cr (VI)	31.5	[67]
14	Fe_3O_4	Orange G and Acid green	1883 and 1471 for Orange G and Acid green dyes	[68]

While there are notable benefits, it is essential to tackle issues related to environmental safety, cost-effectiveness, and scalability. Future investigations should prioritize improving material durability, minimizing harmful effects, and incorporating nanomaterials into current wastewater management frameworks.

Carbon nanotubes have demonstrated significant efficacy, as evidenced by a study indicating a 91.71% removal efficiency for Ismate violet 2R dye at a concentration of 10 mg/L over a period of 120 minutes [93]. In the field of nano electronics, carbon nanotubes are distinguished by their remarkable structural, mechanical, electrical, and magnetic properties. Carbon nanotubes are composed mainly of carbon and are characterized by their remarkable stability, minimal reactivity, and notable antioxidant properties. The main instances of these materials consist of carbon nanotubes (CNTs), nanodiamonds, fullerenes, and buckyballs (C60, C20, and C70), along with nanowires. Different categories of nanomaterials encompass ellipsoids, nanowires, buckyballs, nanotubes, and nanodiamonds. The direct conversion of carbon nanotubes (CNTs), along with their notable large aspect ratio, hydrophobic wall surfaces, adsorption capacity, and cylindrical hollow structure, are all attributes of this material that contribute to its use in wastewater treatment [93].

Graphene showcases exceptional thermal and electrical conductivity, characterized by its unique honeycomb structure in two dimensions. In the course of the removal process, both GO and rGO, along with graphene, have been utilized [94]. GO and rGO have demonstrated significant potential in the treatment of wastewater, particularly in the removal of heavy metals [95]. Pyrrolidone reduced graphene oxide (PVP-rGO) nanoparticles have shown impressive adsorption capacity for copper, achieving levels as high as 1698 mg/g [96].

Monolayer graphene serves as the foundation for oxidative reactions that lead to the creation of various components of GO, such as carbonyl, epoxy, and hydroxyl groups. This reveals five potential interactions. The interactions encompass the hydrophobic effect, covalent bonding, electrostatic interactions, hydrogen bonding, and π-π bonding. It is crucial to recognize that these interactions play a vital role in the adsorption process and the application of graphene-based materials in wastewater treatment. The substances can be identified by their extensive surface area and abundant oxygen content. Following an investigation comparing GO and rGO, it was observed that the modification of functional groups in rGO led to an increase in its defects and conductivity. Graphene, conversely, showed no alterations of this kind. In the context of removing contaminants, particularly heavy metals such as arsenic, mercury, lead, zinc, copper, and cadmium, materials derived from graphene demonstrate significant efficacy as adsorbents. The application of two effective methods, specifically surface modification and hybridization, enhances both the operational efficiency and the reusability of these materials. Research indicates that these compounds demonstrate significant efficacy in water decontamination processes, as they can effectively eliminate a wide variety of pollutants. The high cost of these materials presents a significant barrier to their use in environmental conservation efforts. Leveraging their adsorption properties, these materials will effectively remove contaminants such as metals and dyes from the environment.

Nonetheless, the application of these nanomaterials in wastewater treatment presents certain obstacles. The introduction of graphene and its derivatives into the environment raises concerns, as they could interact with other pollutants and microorganisms in wastewater treatment facilities, potentially influencing the purification process. Furthermore, although GO has demonstrated potential across various applications, it could adversely impact biological treatment processes [12]. In light of these challenges, the domain of carbon-based nanomaterials for wastewater treatment is experiencing notable growth, as evidenced by a substantial rise in research publications from 50 in 2015 to 158 in 2023 [90]. This trend highlights the continuous progress and opportunities for future enhancements in this field.

Essential Characteristics of Nanoparticles

Nanoparticles exhibit a range of additional properties, encompassing alterations in magnetic, optical, electrical, electronic, thermal, and surface characteristics. At the nanoscale, the properties of materials experience notable changes in comparison to their larger counterparts. All of the aforementioned medical applications leverage specific characteristics, medication distribution, and environmental remediation, as explored in article [97].

Characteristics of Surfaces

The extent of particle aggregation and the actual size of the particles are primarily influenced by surface characteristics, including surface energy, interactions between particles, and modifications to the surface. The influences of these forces are independent of gravitational forces; instead, they are governed by alternative interactions, including those between Van der Waals forces. Activated carbons do not meet the criteria established by the existing definitions of nanomaterials. Scientific literature indicates that activated carbons possess a considerable surface area, yet they do not fall under the classification of nanomaterials. They utilize highly permeable structures instead. The surface characteristics of certain nanoparticles have a direct impact on the biological identity of a nanomaterial. This behavior is crucial for biological applications. Nanoparticles possess the ability to retain quantum properties due to their elevated surface-to-volume ratio [98].

Due to their extensive surface area, nanoparticles can efficiently eliminate a range of contaminants, such as heavy metals, organic compounds, and harmful microbes, by offering numerous sites for adsorption and catalytic reactions. Tailored and modified characteristics enhance precision, enabling nanoparticles to focus on specific contaminants. Their adaptability can be linked to various mechanisms, including magnetic separation, adsorption, photocatalysis, and antibacterial characteristics. The properties of nanoparticles position them as a compelling option for effective, eco-friendly, and scalable water filtration solutions [99]. Furthermore, the efficacy of nanoparticles in water purification is also affected by their surface charge. In water-based drilling fluids, positively charged nanoparticles demonstrated enhanced filtering capabilities, resulting in decreased filtrate quantities [100]. Moreover, the predominant factor influencing nanoparticle adsorption to surfaces is electrostatic interactions, which can be modulated by adjusting the suspension's pH in accordance with the isoelectric points of both the nanoparticles and the support material [101].

Magnetic Properties

The distinctive and appealing nature of nanoparticles is attributed to their extensive surface area. Magnetic nanoparticles are utilized in various applications, including cooling, visualization, bioprocessing, advanced cache storage materials, magnetic memory devices, and magnetic printing. Massive magnetoresistance consists of a nanoscale multilayer structure that includes ferromagnetic materials such as iron, cobalt, and nickel, along with non-magnetic substrates like chromium and copper, serving as data memory in storage systems [32].

The ability to easily separate and repurpose these nanoparticles without major structural or functional alterations highlights their magnetic properties, which are crucial for the cost-effective and environmentally sustainable elimination of pollutants from water [102]. The unique magnetic properties of magnetic nanoparticles present significant advantages in water treatment applications, enabling efficient separation, recovery, and repurposing of adsorbent materials. This reduces the environmental footprint and operational costs while simultaneously enhancing the overall effectiveness of water treatment [103].

In contrast to traditional column-bed filtering methods, this magnetic separability allows for simple and energy-efficient instrumentation [104]. Furthermore, external magnetic fields have the capability to influence magnetic nanocomposites because of their superparamagnetic properties, particularly those derived from iron oxides such as magnetite. This feature facilitates the easy extraction of nanoparticles from treated water, allowing for their recovery and reuse in multiple treatment cycles [37]. Copper ferrite ($CuFe_2O_4$) nanoparticles serve as a cost-effective option for water purification, as they can be easily extracted from treated water with the aid of an external magnetic field and can be reused multiple times across several cycles [77].

Characteristics of Light Interaction

The connection between orbital energy and the nanoscale of electronic structure is significant. The presence of these electrons enables the development of optical systems and facilitates the absorption of electromagnetic waves. The optical characteristics of various metals and semiconductors can significantly differ from each other.

Nanoparticles play a significant role in water treatment applications due to their unique optical properties, particularly their ability to effectively absorb light and convert it into heat. The restricted surface plasmon resonance exhibited by nanoparticles, especially those made of metal, imparts remarkable optical properties that allow for efficient light absorption and conversion into heat. Due to their ability to convert light into heat, nanoparticles are highly suitable for solar-powered water treatment systems like direct absorption solar collectors (DASC) [105]. For instance, research has shown that nanoparticles composed of titanium, nickel, molybdenum, and palladium, with radii of approximately 75 nm, demonstrate effectiveness in absorbing solar energy and generating heat. It is noteworthy that various factors such as particle size, shape, material composition, and surrounding media can be utilized to modify the optical properties of nanoparticles [106]. For example, it was noted that with an increase in particle size, the colloidal tension of gold nanoparticles transitions from a deep red to a rich yellow hue. Furthermore, ZnO and TiO_2 nanoparticles were investigated for their optical properties by Santosh and colleagues through DFT analysis, revealing significant potential as efficient UV-absorbing and photocatalytic materials. Consequently, they can serve as effective microbial disinfectants in the treatment of wastewater [107].

Characteristics Related to Electrical and Electronic Systems

The electrical characteristics of a product are greatly affected by various factors, such as dispersion, electronic influences, and alterations in the object's substructure. A decrease in measurement below a certain threshold, specifically below the De Broglie wavelength, results in changes to the electronic structure, evidenced by a wider bandgap and reduced electrical conductivity. As the size of the material increases, there is a notable decrease in imperfections, resulting in lower resistance and improved conductivity [108].

Thermal Characteristics

Thermal conductivity, thermoelectric properties, and specific heat are defining characteristics of nanoparticles.

Thermal conductivity (TC) is two times greater than that of diamonds, which allows CNTs to transfer heat efficiently. The thermal conductivity of nanotubes and their temperature are primarily influenced by phonons. Most solid liquids exhibit lower thermal conductivity compared to metal nanoparticles, while nanoliquids demonstrate significantly higher values. Cu exhibits a thermal conductivity that is seven hundred times greater than that of H_2O and three thousand times that of motor oils at room temperature. Aluminum oxide exhibits a greater thermal conductivity compared to water. Nanofluids exhibit superior thermal conductivity compared to fine-particle fluids and traditional heat transfer fluids. The relationship between surface area and heat transfer efficiency is established [109].

Advanced Approaches in Wastewater Treatment through Nanotechnology

Nanoparticles for the Purification of Water

To effectively manage infections, it is essential to employ both chemical and physical methods to reduce microbial presence on surfaces, both internal and external, to acceptable levels. For disinfection purposes, significant application of ozone, chlorine, reverse osmosis, chlorine dioxide, hypochlorite, and chloramines is typically regarded. Chemical agents used for pathogen disinfection encompass ozone, chlorine, chlorine dioxide, and chloramines. Chlorination has consistently demonstrated effectiveness in combating microorganisms. Ozone, an effective disinfectant, ensures no residues remain. Nonetheless, some individuals occasionally utilize ultraviolet (UV) light as a substitute. Although these approaches demonstrate significant efficacy, they may incur substantial costs or require considerable energy resources. Alternative disinfection methods should demonstrate effectiveness, cost-efficiency, and environmental sustainability. Nanomaterials demonstrate exceptional effectiveness in neutralizing viruses in water, surpassing previous methods due to their large surface areas and improved reactivity. Investigators have employed silver, zinc, copper, polymeric nanoparticles, and carbon nanotubes to address wastewater contamination [110, 111].

Nanometers and Micrometers

Recently, nanoscale and micrometers have surfaced as effective solutions for tackling environmental issues, including the management of water pollution and the monitoring of ecological conditions, which are significant areas of focus. Each of them was extensively utilized to achieve specific objectives in transforming into power for application in machinery. They exhibit unique characteristics, including elevated power, improved speed, self-mixing abilities, and notable control movement, among others. These nano/micrometers are highly regarded for their distinctive characteristics, particularly the active nano-based materials, which significantly improve their effectiveness in converting harmful contaminants into non-toxic forms. Nanomachines offer unique benefits compared to conventional cleaning methods due to their small size and external nano-remediation techniques. Moreover, nano/micromotors have the potential to reduce both the time required for remediation and the overall costs associated with environmental restoration efforts. Conventional treatment methods frequently rely solely on diffusion, requiring external agitation to enhance the wastewater treatment process. Nonetheless, nano/micrometers offer a promising solution for overcoming diffusion limitations by leveraging their inherent mobility capabilities to achieve effective integration. This capability allows for the penetration of diffusion barriers at the nano- and micrometer scale, greatly enhancing the effectiveness of water treatment processes. By harnessing their self-propulsion capabilities, these nano/micrometers could improve water purification efficiency through interaction with the nano/microstructure of materials, thereby increasing the surface area in a manner that promotes an effective process. Motors constructed from polymer capsules demonstrate exceptional efficiency in the process of oil cleanup [112, 113].

A wide array of metals and metal oxides at the nanoscale has been thoroughly employed to eliminate contaminants from wastewater. This is due to the materials' superior effectiveness and lower cost compared to alternative options. Nano zero-valent iron (nZVI), Fe_2O_3, Al_2O_3, MnO, MgO, CeO_2, ZnO, and TiO_2 represent a selection of the commonly utilized metal oxide nanoparticles in this process [114]. For example, to facilitate the detection of silver ions, Au/Pt nanomotors employ a method that generates acceleration through the use of platinum.

Nanomembranes

A nanomembrane, made up of different nanofibers, is employed to eliminate unacceptable nanoparticles from a liquid-liquid medium. The implementation of a strategy that operates through rapid elimination is prone to the accumulation of fouling and bears a resemblance to a method referred to as reverse osmosis. Membranes composed of polymers are predominantly employed in the fabrication of diverse nanomembranes. Water treatment utilizes membranes that are permeable to water, enabling processes such as reverse osmosis, ultrafiltration, and nanofiltration, among others. The membrane consists of a porous material and a layer that undergoes fusion. The composite layer comprises a material that incorporates carbon distributed throughout the polymer matrix. Carbon nanotubes serve as prime examples of materials exhibiting antimicrobial properties, effectively minimizing the chances of mechanical failures by decreasing fouling and inhibiting biofilm formation. To enhance silver, a polymer is utilized, leading to a membrane made of polymers that demonstrates antimicrobial properties. Nanomembranes have been incorporated into wastewater treatment owing to the various benefits they offer. In this specific application, these attributes encompass a strong level of reliability, uniformity, enhanced performance, and efficiency, along with swift execution, user-friendliness, and a notable order of responsiveness. Consequently, they are the preferred option. Nanomaterials can be synthesized to function as stationary membranes through the utilization of hydrogen peroxide. This chemical generates free radical ions that can efficiently eliminate organic contaminants, such as chlorides originating from groundwater.

This method has consistently proven to be highly effective across various industrial and commercial settings. Nanomembranes have been developed mainly for the purpose of eliminating toxins from water environments. Nanomembranes offer considerable advantages over traditional filtration methods. Unlike traditional approaches, calcium and magnesium necessitate an extra ion for balance, with sodium ions frequently functioning as the exchangers. Nonetheless, the application of nanomembranes makes such replacement unnecessary. Due to their remarkable attributes, including high permeability, antibacterial properties, and superior porosity, nanofiber membranes find utility in numerous applications, such as prefiltration, ultrafiltration, separation filtration devices, water management, and filter cartridges. Nanocomposite membranes exhibit several advantageous properties, such as elevated water permeability, robust thermal and mechanical resistance, improved hydrophilicity, and increased resistance to contamination. Ultra-filtering utilizes membranes that self-assemble, distinguished by uniform nanopores. Aquaporin-based membranes demonstrate improved ionic selectivity, rendering them particularly efficient for applications in low-pressure desalination processes. Nanofiltration membranes are widely employed for eliminating color and odor, in addition to decreasing hardness. The optimal performance of nanomembranes is constrained by particular factors. To tackle these challenges, it is essential to concentrate on the nanomembrane's selectivity. An upgrade is essential to mitigate the fouling of the nanomembranes' resistivity [115-118].

Nano Photocatalysts

Nano photocatalysts enhance the reactivity of catalysts, leading to their widespread use in wastewater treatment applications. This phenomenon can be attributed to the rising ratio of surface area to volume and the inherent characteristics that depend on shape. Nano photocatalysts enhance oxidation, thereby removing contaminants by increasing the presence of oxidizing species at the material's surface. Nano photocatalysts effectively break down organic pollutants.

The process of photocatalytic degradation encompasses the following steps:

a) the initiation of the photocatalyst,

b) the generation of electron-hole pairs,

c) the generation of ions in moisture, the ionosorption of oxygen, the protonation of superoxide, and the breakdown of contaminants.

Nanoparticles, encompassing semiconductors and zero-valence metals, play a crucial role in the treatment of effluents that consist of azo dyes, chlorpyrifos, nitroaromatics, and organochlorine pesticides. Nano photocatalysts such as ZnO, SiO_2, Al_2O_3, and TiO_2 are extensively utilized. TiO_2 nanoparticles are acknowledged as a highly efficient nanophotocatalyst due to their cost-effectiveness, non-toxic nature, availability, and chemical resilience. The anatase form of TiO_2 is regarded as a highly effective nanophotocatalyst material. ZnO demonstrates notable effectiveness in the removal of effluent and the recycling of water. ZnO nanoparticles combined with Pd have demonstrated effectiveness in wastewater treatment and the elimination of *E. coli*, due to the strong photocatalytic properties they exhibit. Nano photocatalysis is categorized into two distinct types: homogeneous and heterogeneous. Contemporary methods for water purification frequently employ heterogeneous photocatalysis as a technique for achieving clean water. To realize heterogeneous photocatalysis, it is essential to create an interface between a solid photocatalyst, which can be either a semiconductor or a metal, and a liquid phase that encompasses the reactants and products of the reaction. Nano photocatalysts exhibit impressive effectiveness and efficiency in water purification, significantly aiding in the removal of harmful organic compounds at a temperature of 25°C. Nano-sized materials offer several benefits, with the most significant being the nano-dimensional effect. This effect enhances the energy bandgap while concurrently reducing the size of the particles. Moreover, photodegradation offers several advantages, including its cost-effectiveness and potential for reuse, and it generally leads to a complete breakdown. Nano photocatalysts can initiate chemical reactions upon exposure to light, allowing for a wide array of applications across different industries. Nano photocatalysts encounter challenges like toxicity and the extraction of catalysts from mixtures, even with the considerable advancements achieved in this field. The challenges present limitations that hinder the broader application of nano photocatalysts and impede their ability to realize their full potential at larger scales [119, 120].

Nanosorbents

Nanosorbents exhibit remarkable sorption abilities, making them highly effective materials for water treatment applications. Widely acknowledged nanosorbents include materials derived from carbon, polymers, and various metal or metal oxide nanomaterials (Fig. 3). Their significant physicochemical properties, which offer specific advantages in pollution removal processes, are the cause of the increasing interest. These characteristics distinguish them from conventional sorbents in multiple aspects. An ideal sorbent features an extensive surface area, rapid adsorption kinetics, and clearly defined adsorption and equilibrium phases to effectively address contaminants in a timely manner. Nanomaterials, such as nanosorbents, have attracted attention due to their nano-scale dimensions, enabling rapid adsorption and shorter treatment durations. Water purification employs nanoparticles as nanosorbents to eliminate both organic and inorganic contaminants effectively. The toxicity of wastewater treatment is diminished through the use of composite materials, such as Ag/polyaniline, Ag/carbon, and C/TiO_2. Carbon nanotubes and other carbon-based materials exhibit remarkable properties. The synthesis process dictates the classification of carbon nanotubes (CNTs) as either single-walled or multi-walled. Their cylindrical nanostructure improves adsorption efficiency. Their extensive surface area and numerous adsorption sites contribute to their efficacy in removing pollutants. To enhance the adsorption potential of carbon nanotubes (CNT), it is essential to stabilize them in order to minimize aggregation, thereby preserving surface-active sites. Dendrimers and various polymeric nanosorbents effectively capture organic contaminants and heavy metals from contaminated water sources. The material exhibits unique attributes such as an extensive surface area, the existence of functional groups, and adjustable properties, all of which improve its effectiveness in contaminant removal processes. Diverse nanosorbents exhibit distinct treatment capabilities: carbon-based nanosorbents excel in nickel ion removal, metal oxides are utilized for extracting various heavier metals, polymeric fibers are employed in the remediation of arsenic and other water pollutants, and nano clays prove effective in the removal of hydrocarbons and dyes.

Magnetic nanosorbents play a crucial role in water treatment systems, serving as a targeted method for the removal of various organic pollutants. Methods employing magnetic filtration show promise in effectively eliminating organic contaminants. Magnetic separation nanosorbents are developed by applying ligands to magnetic nanoparticles, which bestow a distinct affinity for specific target pollutants. A range of reports outlines comprehensive methodologies for the regeneration of these nanosorbents, including the use of cleaning agents, ion exchange processes, and magnetic forces.

Regenerated nanosorbents show promise for enhanced market feasibility and economic efficiency. Carbon-based nanomaterials present specific health risks that require careful consideration. The findings of the study reveal that modifications to the surface, the use of chemical stabilization agents, and the application of nano adsorbents all influence the concentrations of encountered toxins. Therefore, it is crucial to explore options for water treatment and to create innovative adsorbents that demonstrate lower toxicity [116-118].

Table 2. presents a comprehensive overview of various nanomaterials employed in wastewater treatment, highlighting the specific pollutants they address and their corresponding removal efficiencies. This table highlights the efficacy of different nanomaterials in tackling contaminants, demonstrating

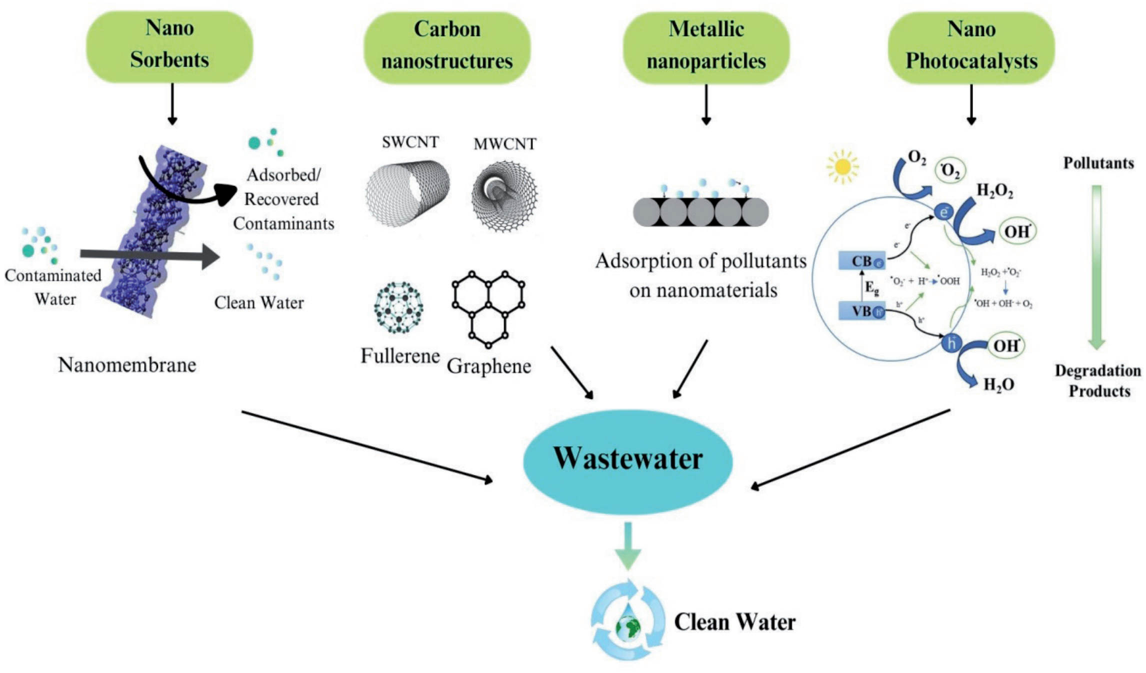


Fig. 3. Nanotechnology for wastewater treatment [120, 121].

Table 2. Key nanomaterials and their performance in wastewater treatment.

Nanomaterial	Pollutant Removed	Removal Efficiency (%)
TiO_2 Nanoparticles	Dyes, Heavy Metals	85-95
Fe_3O_4 Nanoparticles	Arsenic, Chromium	80-90
Carbon Nanotubes	Organic Pollutants	75-85
Silver Nanoparticles	Microbial Contaminants	90-99

their potential for sustainable water purification techniques.

Results and Discussion

Real-World Applications of Nanotechnology in Wastewater Treatment

Nanotechnology has demonstrated considerable promise in the treatment of wastewater, especially in the effective removal of heavy metals, organic pollutants, and microbial contaminants through practical applications. Nanocomposites, including graphene-based materials and metal oxide nanoparticles, have been effectively incorporated into filtration membranes to improve the efficiency of contaminant removal. Practical implementations encompass the utilization of membranes coated with silver nanoparticles for antimicrobial disinfection and the application of iron-based nanocomposites for the removal of arsenic and fluoride from drinking water [45, 50].

Industries have embraced titanium dioxide (TiO_2) photocatalysts for the degradation of organic pollutants in wastewater, a technique commonly utilized in the treatment of effluents from textiles and pharmaceuticals [11, 33]. Magnetic nanoparticles have been employed for the swift separation of pollutants, thanks to their convenient recovery through external magnetic fields [49]. Additionally, carbon nanotube-based adsorbents have been utilized in large-scale wastewater treatment facilities for the purpose of heavy metal adsorption [41].

Pilot-scale studies have shown the practicality of using nanomaterial-based treatment in municipal wastewater facilities, emphasizing their capability to supplant traditional methods [39]. Even with these developments, widespread implementation encounters obstacles, including elevated production expenses, possible environmental concerns, and challenges related to scalability. Ongoing investigation into economical synthesis and environmentally friendly disposal techniques is essential for wider adoption [51].

The application of nanotechnology in wastewater treatment signifies a groundbreaking method for securing access to clean water, especially in areas experiencing water shortages.

Challenges and Future Prospects

Nanotechnology has made remarkable progress across various fields, particularly in medical research, and now holds an essential position in wastewater treatment thanks to the distinctive characteristics of nanomaterials. These materials exhibit impressive effectiveness in eliminating contaminants; nonetheless, their broader implementation encounters various obstacles. A significant constraint is the elevated expense of nanomaterials, which limits their application, especially in areas with limited resources. To address this challenge, subsequent investigations should prioritize economical synthesis approaches and methods for large-scale production. Improving the economic viability of treatments utilizing nanomaterials will facilitate wider adoption, leading to enhanced water quality and accessibility. A further challenge lies in the stability and longevity of nanomaterials when subjected to different environmental conditions. Some nanomaterials might deteriorate or change form, which can influence their effectiveness in managing wastewater. The focus of the investigation should be on advancing composites or surface modifications to improve the durability of nanoparticles in challenging water treatment conditions. Expanding nanomaterial-based treatment technologies from controlled environments to practical use introduces further technical hurdles, including aggregation, fouling, and operational intricacies. Joint initiatives between educational institutions and the private sector are crucial to overcoming these obstacles and enabling widespread adoption.

Moreover, although nanoparticles demonstrate significant adsorption capabilities, their capacity to selectively target particular pollutants within intricate wastewater streams continues to pose a challenge. Future investigations ought to concentrate on the development of functionalized nanoparticles or nanocomposites that exhibit improved selectivity for contaminants while reducing interference from non-target substances. Finally, it is essential to conduct a comprehensive evaluation of the possible health and environmental hazards linked to nanomaterials, such as toxicity and bioaccumulation. Creating consistent risk assessment frameworks will be essential for guaranteeing the safe and sustainable use of nanotechnology in wastewater treatment, while also reducing unintended ecological and human health consequences [122-124].

Environmental Impact of Nanocomposites

The additional waste is generated from non-utilized nanocomposite membranes during the adsorption process, which cannot be recycled. Even at minimal concentrations, adsorbent materials that include heavy metals pose a threat to both the ecosystem and human health. The challenges increase as the size of the adsorbent expands. Through the application of catalysts or redox reagents, nanocomposites effectively break down environmental pollutants.

Catalysis has the potential to introduce harmful substances or contaminate pristine water sources with its byproducts. Should the nanocomposite membrane experience leakage, the water could potentially contain harmful substances. Nanomaterials will enter the environment through both intentional and unintentional releases, such as air emissions and waste streams from industrial facilities, leading to contamination of surface and groundwater. Their deposition in the respiratory system can lead to neurotoxicity influenced by nanostructures due to factors such as substantial surface area, elevated surface activity, unique shapes, small diameters, or subsequent fragmentation into smaller particles. Nanoparticles are deposited effectively in healthy lungs and, to a greater extent, in individuals with asthma and COPD. The absorption of these particles in living organisms could pose a threat to ecosystems. In agricultural and various soil-contact applications, nanocomposites have the potential to alter soil properties. This could influence the microbial community, nutrient dynamics, and overall soil vitality. The environmental implications of nanocomposites are extensive, and ongoing research continues to explore their effects, complicating the processes of regulation and monitoring. Establishing consistent testing protocols and regulatory frameworks is crucial for safeguarding the environment. Furthermore, concerns regarding the potential environmental release of nanomaterials during wastewater treatment processes present a significant obstacle. A comprehensive understanding of the behaviors, fate, and long-term impacts of nanoparticles in aquatic environments that are taking them in is crucial for mitigating this risk. Implementing comprehensive monitoring systems and risk assessment methods is essential to ensure the safe utilization and disposal of nanomaterials. This will lead to a decrease in the potential ecological impacts that were encountered earlier [125-128].

Conclusions

The capacity of nanomaterials to transform wastewater treatment and address global water challenges with remarkable efficiency and environmental sustainability is substantial. The rapid advancements in nanotechnology and the creation of engineered nanoparticles have significantly enhanced environmental remediation initiatives, facilitating the efficient extraction of a range of pollutants, such as organic contaminants, heavy metals, pesticides, and microbial agents. These materials, characterized by their vast surface area, tunable reactivity, and remarkable adsorption properties, are essential in modern purification methods.

This study emphasizes the notable progress in nanomaterials, including iron oxide, nano-silver, carbon-based nanostructures (like graphene, nanotubes, and fullerenes), and nanocomposites, aimed at tackling water pollution. Utilizing the unique physicochemical properties of these materials can enhance the efficiency, cost-effectiveness, and environmental sustainability of wastewater treatment.

Nonetheless, the extensive application of nanotechnology in water treatment encounters significant obstacles. The challenge of scalability persists, as the mass production of nanomaterials while ensuring their efficacy is frequently intricate and expensive. Moreover, issues related to environmental hazards, such as the toxicity of nanoparticles, their long-term effects on ecosystems, and challenges associated with disposal, necessitate a comprehensive examination. Regulatory frameworks need to adapt to tackle these uncertainties while guaranteeing the safe and ethical use of nanomaterials.

Addressing these challenges requires collaborative research initiatives, eco-friendly production techniques, and policy-oriented strategies to promote the responsible and extensive integration of nanotechnology. Although nanotechnology presents significant potential for a sustainable future with reliable water resources, it is essential to tackle these limitations for its effective and enduring implementation. Through the promotion of innovation, teamwork, and sustainable progress, nanomaterials have the potential to significantly influence the evolution of cutting-edge water purification technologies, guaranteeing clean and accessible water for generations to come.

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Conflict of interest

There are no conflicts to declare.

References

1. WHO. Drinking-water. Available online: https://www.who.int/news-room/fact-sheets/detail/drinking-water (accessed Jan 5, 2025). **2023**.

2. ZHOU Y., WANG T., ZHI D., GUO B., ZHOU Y., NIE J., LUO L. Applications of nanoscale zero-valent iron and its composites to the removal of antibiotics: a review. Journal of Materials Science. **54** (19), 12171, **2019**.
3. WITKOWSKA D., SLOWIK J., CHILICKA K. Heavy Metals and Human Health: Possible Exposure Pathways and the Competition for Protein Binding Sites. Molecules. **26** (19), 6060, **2021**.
4. SAGADEVEN S., FATIMAH I., EGBOSIUB T.C., ALSHAHATEET S.F., LETT J.A., WELDEGEBRIEAL G.K., LE M.V., JOHAN M.R. Photocatalytic Efficiency of Titanium Dioxide for Dyes and Heavy Metals Removal from Wastewater. Bulletin of Chemical Reaction Engineering and Catalysis. **17** (2), 430, **2022**.
5. EBELE A.J., ABDALLAH M.A., HARRAD S. Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. Emerging Contaminants. **3** (1), 1, **2017**.
6. OSUOHA J.O., ANYANWU B.O., EJILEUGHA C. Pharmaceuticals and personal care products as emerging contaminants: Need for combined treatment strategy. Journal of Hazardous Materials Advances. **9**, 100206, **2023**.
7. UMAR K., HAQUE M.M., MIR N.A., MUNEER M., FAROOQI I.H. Titanium Dioxide-mediated Photocatalysed Mineralization of Two Selected Organic Pollutants in Aqueous Suspensions. Journal of Advanced Oxidation Technologies. **16** (2), 252, **2013**.
8. EPELLE E.I., OKOYE P.U., RODDY S., GUNES B., OKOLIE J.A. Advances in the Applications of Nanomaterials for Wastewater Treatment. Environments. **9** (11), 141, **2022**.
9. GAUTAM S., SAINI G. Use of natural coagulants for industrial wastewater treatment. Global Journal of Environmental Science and Management. **6** (4), 553, **2020**.
10. ZAGKLIS D.P., BAMPOS G. Tertiary Wastewater Treatment Technologies: A Review of Technical, Economic, and Life Cycle Aspects. Processes. **10** (11), 2304, **2022**.
11. NISHU D., KUMAR S. Smart and innovative nanotechnology applications for water purification. Hybrid Advances. **3**, 100044, **2023**.
12. BHAT S.A., SHER F., HAMEED M., BASHIR O., KUMAR R., VO D.V.N., AHAMAD P., LIMA E.C. Sustainable nanotechnology-based wastewater treatment strategies: achievements, challenges and future perspectives. Chemosphere. **288**, 132606, **2022**.
13. BISARIA K., SINHA S., SINGH R., IQBAL H.M.N. Recent advances in structural modifications of photo-catalysts for organic pollutants degradation – A comprehensive review. Chemosphere. **284**, 131263, **2021**.
14. SOREN S., PANDA P., CHAKROBORTY S. Metal oxide nanofiller-introduced polymer-based nanocomposite dielectrics for advanced energy storage devices. In: Emerging Nanodielectric Materials for Energy Storage Nanostructure Science and Technology, Chapter 15, pp 415, Publisher Springer, **2023**.
15. SEKOAI P.T., OUMA C.N.M., DU PREEZ S.P., MODISHA P., ENGELBRECHT N., BESSARABOY D.G., GHIMIRE A. Application of nanoparticles in biofuels: An overview. Fuel. **237**, 380, **2019**.
16. CRINI G., LICHTFOUSE E. Advantages and disadvantages of techniques used for wastewater treatment. Environmental Chemistry Letters. **17**, 145, **2019**.
17. KESARI K.K., VERMA H.N., BEHARI J. Physical methods in wastewater treatment. International Journal of Environmental Technology and Management. **14**, 43, **2011**.
18. MUSA M.A., IDRUS S. Physical and biological treatment technologies of slaughterhouse wastewater: A review. Sustainability. **13**, 4656, **2021**.
19. BARRED-DAMAS S., IBORRA-CLAR M.I., BES-PIA A., ALCAINA-MIRANDA M.I., MENDOZA-ROCA J.A., IBORRA-CLAR A. Study of preozonation influence on the physical-chemical treatment of textile wastewater. Desalination. **182**, 267, **2005**.
20. SRAVAN J.S., MATSAKAS L., SARKAR O. Advances in biological wastewater treatment processes: Focus on low-carbon energy and resource recovery in biorefinery context. Bioengineering. **11**, 281, **2024**.
21. KHALIDI-IDRISSI A., MADINZI A., ANOUZLA A., PALA A., MOUHIR L., KADMI Y., SOUABI S. Recent advances in the biological treatment of wastewater rich in emerging pollutants produced by pharmaceutical industrial discharges. International Journal of Environmental Science and Technology. **20**, 11719, **2023**.
22. BHATIA R.K., SAKHUJA D., MUNDHE S., WALIA A. Renewable energy products through bioremediation of wastewater. Sustainability. **12**, 7501, **2020**.
23. CAMEL V., BERMOND A. The use of ozone and associated oxidation processes in drinking water treatment. Water Research. **32**, 3208, **1998**.
24. RIGOBELLO E.S., DANTAS A.D.B., Di BERNADO L., VIEIRA E.M. Removal of diclofenac by conventional drinking water treatment processes and granular activated carbon filtration. Chemosphere. **92**, 184, **2013**.
25. ZHANG K., XIE Y., YE Z., ZHANG W., ZHANG Q., YU X., FENG M. Unravelling the role of iodide in periodate-based water decontamination: Accelerated selective oxidation and formation of iodinated products. Chemical Engineering Journal. **461**, 141879, **2023**.
26. CORNELISSEN E.R., HARMSEN D.J.H., BLANKERT B., WESSELS L.P., VAN DER MEER W.G.J. Effect of minimal pre-treatment on reverse osmosis using surface water as a source. Desalination. **509**, 115056, **2021**.
27. KASHIF M., SABRI M.A., ZHANG N., BANAT F. Graphene: A diamond hammer for cracking hard nuts in reverse osmosis desalination membranes. Desalination. **581**, 117552, **2024**.
28. IKEHATA K., ZHAO Y., KULKARNI H.V., LI Y., SNYDER S.A., ISHIDA K.P., ANDERSON M.A. Water recovery from advanced water purification facility reverse osmosis concentrate by photobiological treatment followed by secondary reverse osmosis. Environmental Science & Technology. **52**, 8588, **2018**.
29. DING M., BANNURU K. K. R., WANG Y., GUO L., BAJI A., YANG H. Y. Free-standing electrodes derived from metal–organic frameworks/nanofibers hybrids for membrane capacitive deionization. Advanced Materials Technologies. **3**, 1800135, **2018**.
30. CHEN T.H., YEH K.H., LIN C.F., LEE M., HOU C.H. Technological and economic perspectives of membrane capacitive deionization (MCDI) systems in high-tech industries: From tap water purification to wastewater reclamation for water sustainability. Resources, Conservation & Recycling. **177**, 106012, **2022**.
31. LEE B., OH C., AN J., YEON S., OH H.J. Optimizing operational conditions of pilot-scale membrane capacitive deionization system. Sustainability. **15** (24), 16809, **2023**.
32. LESTER Y., SHAULSKY E., EPSZEIN R., ZUCKER I. Capacitive deionization for simultaneous removal of

salt and uncharged organic contaminants from water. Separation and Purification Technology. **237**, 116388, **2020**.
33. CHEN W., HE X., JIANG Z., LI B., LI X. YAN, LIN L. A capacitive deionization and electro-oxidation hybrid system for simultaneous removal of heavy metals and organics from wastewater. Chemical Engineering Journal. **451**, 139071, **2023**.
34. JABBAR K.Q., BARZINIY A.A., HAMAD S.M. Iron oxide nanoparticles: preparation methods, functions, adsorption, and coagulation/flocculation in wastewater treatment. Environmental Nanotechnology Monitoring & Management. **17**, 100661, **2022**.
35. KIM D.K., ZHANG Y., VOIT W., RAO K.V., KEHR J., BJELKE B., MUHMMED M. Superparamagnetic iron oxide nanoparticles for bio-medical applications. Scripta Materialia. **44**, 1713, **2001**.
36. LIM J.K., YEAP S.P., LOW S.C. Challenges associated with magnetic separation of nanomaterials at low field gradient. Separation and Purification Technology. **123**, 171, **2014**.
37. MARTINEZ-BOUBETA C., SIMEONIDIS K. Magnetic nanoparticles for water purification. In: Nanoscale Materials in Water Purification, p. 521, Elsevier, **2019**.
38. JIANG M., QI Y., LIU H., CHEN Y. The role of nanomaterials and nanotechnologies in wastewater treatment: a bibliometric analysis. Nanoscale Research Letters. **13**, 1, **2018**.
39. XU P., ZENG G.M., HUANG D.L., FENG C.L., HU S., ZHAO M.H., LAI C., WEI Z., HUANG C., XIE G.X., LIU Z.F. Use of iron oxide nanomaterials in wastewater treatment: a review. Science of The Total Environment. **424**, 1, **2012**.
40. ALI I., PENG C., NAZ I., AMJED M.A. Water purification using magnetic nanomaterials: an overview. Nanotechnology in the Life Sciences (Magnetic Nanostructures). **161**, **2019**.
41. KHAISHEH M., ELHENAWY S., ALMOMANI F., AL-GHOUTI M., HASSAN M.K., HAMEED B.H. Recent progress on nanomaterial-based membranes for water treatment. Membranes. **11**, 995, **2021**.
42. UTKARSH C., SENTHIL K.S., VISHAK S., VISHNU C., ASHESH M.A., MOHAMMED Z.M., MANIKANDAN M., VELMURUGAN P. A review of the function of using carbon nanomaterials in membrane filtration for contaminant removal from wastewater. Materials Research Express. **9**, 012003, **2022**.
43. KIM J., VAN DER B. The use of nanoparticles in polymeric and ceramic membrane structures: review of manufacturing procedures and performance improvement for water treatment. Environmental Pollution. **158**, 2335, **2010**.
44. SAVAGE N., DIALLO M.S. Nanomaterials and water purification: opportunities and challenges. Journal of Nanoparticle Research. **7**, 331, **2005**.
45. ALLAHKARAMI E., ALLAHKARAMI E. A mini-review on nano-enabled solutions for wastewater treatment: addressing disinfection by-products. Current Opinion in Environmental Science & Health. **38**, 100545, **2024**.
46. YU L., RUAN S., XU X., ZOU R., HU J. One-dimensional nanomaterial-assembled macroscopic membranes for water treatment. Nano Today. **17**, 79, **2017**.
47. OJHA A. Nanomaterials for removal of waterborne pathogens: opportunities and challenges. In: Waterborne Pathogens: Detection and Treatment, Chapter **19**, 385, Elsevier Ltd., Amsterdam, **2020**.
48. GHASEMZADEH G., MOMENPOUR M., OMIDI F., HOSSEINI M.R., AHANI M., BARZEGARI A. Applications of nanomaterials in water treatment and environmental remediation. Frontiers of Environmental Science & Engineering. **8**, 471, **2014**.
49. FU W., LIU Z., YANG Z., LI Y., PAN B. Confined iron-based nanomaterials for water decontamination: fundamentals, applications, and challenges. Fundamental Research. **5** (2), 612, **2023**.
50. TAMJIDI S., MOGHADAS B.K., ESMAEILI H., SHAKERIAN K.F., GHOLAMI G., GHASEMI M. Improving the surface properties of adsorbents by surfactants and their role in the removal of toxic metals from wastewater: a review study. Process Safety and Environmental Protection. **148**, 775, **2021**.
51. SARAVANAN A., SENTHIL K.P., JEEVANANTHAM S., KARISHMA S., TAJSABREEN B., YAASHIKAA P.R., RESHMA B. Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. Chemosphere. **280**, 130595, **2021**.
52. YOUNAS F., MUSTAFA A., FAROOQI Z.U.R., WANG X., YOUNAS S., MOHIYUDDIN W., HAMEED M.A., ABRAR M.M., MAITLO A.A., NOREEN S., HUSSAIN M.M. Current and Emerging Adsorbent Technologies for Wastewater Treatment: Trends, Limitations, and Environmental Implications. Water MDPI. **13**, 215, **2021**.
53. ALI M.E., HOQUE M.E., SAFDAR H.S.K., BISWAS M.C. Nano adsorbents for wastewater treatment: next generation biotechnological solution. International Journal of Environmental Science and Technology. **17**, 4095, **2020**.
54. MANGLA D., ANNU SHARMA A., IKRAM S. Critical review on adsorptive removal of antibiotics: Present situation, challenges and future perspective. Journal of Hazardous Materials. **425**, 127946, **2022**.
55. PATEL M., KUMAR R., KISHOR K., MLSNA T., PITTMAN C.U. Jr., MOHAN D. Pharmaceuticals of emerging concern in aquatic systems: chemistry, occurrence, effects, and removal methods. Chemical Reviews. **119** (6), 3510, **2019**.
56. HOU C., YU H., ZHANG Q., LI Y., WANG H. Preparation and Magnetitic Property Analysis of Monodisperse Co-Zn Ferrite Nanospheres. Journal of Alloys and Compounds. **491** (1-2), 431, **2010**.
57. SHAFI K.V.P.M., GEDANKEN A., PROZOROV R., BALOGH J. Sonochemical Preparation and Size-Dependent Properties of Nanostructured $CoFe_2O_4$ Particles. Chemistry of Materials. **10**, 3445, **1998**.
58. CHANDEKAR K.V., KANT K.M. Effect of size and shape dependent anisotropy on superparamagnetic property of $CoFe_2O_4$ nanoparticles and nanoplatelets. Physica B: Condensed Matter. **520**, 152, **2017**.
59. WU M., XIONG Y., JIA Y., NIU H., QI H., YE J., CHREM Q. Magnetic field-assisted hydrothermal growth of chain-like nanostructure of magnetite. Chemical Physics Letters. **401**(4-6), 374, **2005**.
60. DASCALI G., POPESCU T., FEDER M., CALTUN O.F. Structural, electric and magnetic properties of $CoFe_{1.8}RE_{0.2}O_4$ (RE=Dy, Gd, La) bulk materials. Journal of Magnetism and Magnetic Materials. **333**, 69, **2013**.
61. OLADOJA N.A., HU S., DREWES J.E., HELMREICH B. Insight into the defluoridation efficiency of nano magnesium oxide in groundwater system contaminated with hexavalent chromium and fluoride. Separation and Purification Technology. **162**, 195, **2016**.

62. ADELI M., YAMINI Y., FARAJI M. Removal of copper, nickel and zinc by sodium dodecyl sulphate coated magnetite nanoparticles from water and wastewater samples. Arabian Journal of Chemistry. **10**, S514, **2017**.
63. BANERJEE S., DUBEY S., GAUTAM R.K., CHATTOPADHYAYA M.C., SHARMA Y.C. Adsorption characteristics of alumina nanoparticles for the removal of hazardous dye, Orange G from aqueous solutions. Arabian Journal of Chemistry. **12**, 5339, **2019**.
64. KIANI G., DOSTALI M., ROSTAMI A., KHATAEE A.R. Adsorption studies on the removal of Malachite Green from aqueous solutions onto halloysite nanotubes. Applied Clay Science. **54**, 1, 34, **2011**.
65. ÖZLEM K.A.Z., YURUM Y. Synthesis and characterization of anatase nano adsorbent and application in removal of lead, copper and arsenic from water. Chemical Engineering Journal. **225**, 625, **2013**.
66. HU J., CHEM G., LO I.M.C. Removal and recovery of Cr (VI) from wastewater by maghemite nanoparticles. Water Research. **39** (18), 4528, **2005**.
67. KANEL S.R., MANNING B., CHARLET L., CHOI H. Removal of Arsenic (III) from Groundwater by Nanoscale Zero-Valent Iron. Environmental Science & Technology. **39**, 1291, **2005**.
68. PHOOMIPAT J., PHAWIDA M., JIRATCHAYA S., PRASIT T., JINDARAT E. Chromium (VI) removal by magnetite nanoparticles immobilized with extracellular polymeric substances extracted from Lysinibacillus sp. WH. Water Environment Research. **96**, e11102, **2024**.
69. HUANG H., HUANG B., HUANG Y., YANG J., YE Y., CHEN Y. Removal of Orange G via environmentally friendly GO@Fe_3O_4-COOH@NH_2-MIL-101(Fe) nanocomposite. Desalination and Water Treatment. **228**, 431, **2021**.
70. BAIG N., KAMMAKAKAM I., FALATH W., KAMMAKAKAM I. Nanomaterials: a review of synthesis methods, properties, recent progress, and challenges. Materials Advances. **2**, 1821, **2021**.
71. AMIN M.T., ALAZBA A.A., MANZOOR U. A review of removal of pollutants from water/wastewater using different types of nanomaterials. Advances in Materials Science and Engineering. **2014** (1), 1, **2014**.
72. ELBANA T., YOUSRY M. Nanomaterials reactivity and applications for wastewater cleanup. Nanotechnology, Food Security and Water Treatment. **255**, **2018**.
73. ZHANG Y., WU B., XU H., LIU H., WANG M., HE Y., PAN B. Nanomaterials-enabled water and wastewater treatment. NanoImpact. **3-4**, 22, **2016**.
74. URSINO C., CASTRO M.R., DRIOLI E., GZARA L., ALBEIRUTY M.H., FIGOLI A. Progress of nanocomposite membranes for water treatment. Membranes (Basel). **8** (2), 18, **2018**.
75. MARCELO L.R., de GOIS J.S., da SILVA A.A., CESAR D.V. Synthesis of iron-based magnetic nanocomposites and applications in adsorption processes for water treatment: a review. Environmental Chemistry Letters. **19** (2), 1229, **2020**.
76. SAHU A., DOSI R., KWIATKOWSKI C., SCHMAL S., POLER J.C. Advanced polymeric nanocomposite membranes for water and wastewater treatment: a comprehensive review. Polymers. **15**, 540, **2023**.
77. NAYL A.A., ABD-ELHAMID A.I., AWWAD N.S., ABDELGAWAD M.A., WU J., MO X., GOMA S.M., ALY A.A., BRASE S. Review of the recent advances in electrospun nanofibers applications in water purification. Polymers. **14**, 1594, **2022**.
78. HUSSAIN N., BILAL M., IQBAL H.M.N. Carbon-based nanomaterials with multipurpose attributes for water treatment: greening the 21st-century nanostructure materials deployment. Biomaterials and Polymers Horizon. **1** (1), 48, **2022**.
79. KUMAR J., JATOI A.S., MAZARI S.A., ALI E.Y., HOSSAIN N., ABRO R., MUBARAK N.M., SABZOI N. Advanced green nanocomposite materials for wastewater treatment: sustainable nanotechnology for environmental remediation, Chapter 12, p.297, Elsevier, **2022**.
80. TRIPATHY J., MISHRA A., PANDEY M., THAKUR R.R., CHAND S., ROUT P.R., SHAHID M.K. Advances in nanoparticles and nanocomposites for water and wastewater treatment: a review. Water. **16** (11), 1481, **2024**.
81. MUKHOPADHYAY R., BHADURI D., SARKAR B., RUSMIN R., HOU D., KHANAM R., SARKAR S. Clay–polymer nanocomposites: Progress and challenges for use in sustainable water treatment. Journal of Hazardous Materials. **383**, 121125, **2020**.
82. AYALEW A.A. A critical review on clay-based nanocomposite particles for application of wastewater treatment. Water Science and Technology. **85**, 3002, **2022**.
83. LU H., WANG J., STOLLER M., WANG T., BAO Y., HAO H. An overview of nanomaterials for water and wastewater treatment. Advances in Materials Science and Engineering. **2016** (1), 1, **2016**.
84. AHMED S.F., MOFIZUR M., AHMED B., MEHNAZ T., MEHJAIN F., MALIAT D., HOANG A.T., SHAFIULLAH G.M. Nanomaterials as a sustainable choice for treating wastewater. Environmental Research. **214**, 113807, **2022**.
85. GUPTA N., YADAV V.K., YADAV K.K., ALWETAISHI M., GNANAMOORTHY G., SINGH B., JEON B.H., CABRAL-PINTU M.M.S., CHOUDHRY N., ALI D., NEJAD Z.D. Recovery of iron nano minerals from sacred incense sticks ash waste collected from temples by wet and dry magnetic separation method. Environmental Technology & Innovation. **25**, 102150, **2022**.
86. KOYO A.S., ALAYA-IBRAHIM S., ABDULKAREEM A.S., ADENIYI O.D., EGBOSIUBA T.C., TIJANI J.O., SAHEED M., OKAFOR B.O., ADEYINKA Y.S. Column adsorption of biological oxygen demand, chemical oxygen demand and total organic carbon from wastewater by magnetite nanoparticles-zeolite A composite. Heliyon. **9** (2), e13095, **2023**.
87. TOLCHA T., GEMECHU T., MEGERSA N. Flower of Typha latifolia as a low-cost adsorbent for quantitative uptake of multiclass pesticide residues from contaminated waters. South African Journal of Chemistry. **73**, 22, **2020**.
88. CHAVALI M.S., NIKOLOVA M.P. Metal oxide nanoparticles and their applications in nanotechnology. SN Applied Sciences. **1 (**6), **2019**.
89. SAIKIA J., GOGOI A., BARUAH S. Nanotechnology for water remediation. Environmental Chemistry for a Sustainable World. **2**, 195, **2019**.
90. GACEM A., MODI S., YADAV V.K., ISLAM S., PATEL A., DAWANE V., JAMEEL M., INWATI G.K., PIPLODE S., SOLANKI V.S., BASNET A. Recent advances in methods for synthesis of carbon nanotubes and carbon nanocomposite and their emerging applications: a descriptive review. Journal of Nanometer. **2022**.
91. THAKUR A., KUMAR A., SINGH A. Adsorptive removal of heavy metals, dyes, and pharmaceuticals: Carbon-based nanomaterials in focus. Carbon. **217**, 118621, **2024**.

92. YILMAZ M., AL-MUSAWI T.J., SALOOT M., KHODADADI KHATIBI A.D., BANIASADI M., BALARAK D. Synthesis of activated carbon from Lemna minor plant and magnetized with iron (III) oxide magnetic nanoparticles and its application in removal of Ciprofloxacin. Biomass Conversion and Biorefinery. **14**, 649, **2024**.
93. BHOL P., YADAV S., ALTAEE A., SAXENA M., MISRA P.K., SAMAL A.K. Graphene-based membranes for water and wastewater treatment: A review. ACS Applied Nano Materials. **4**, 3274, **2021**.
94. BALARAK D., ZAFAIYAN M., IGWEGBE C.A., ONYECHI K.K., IGHALO J.O. Adsorption of Acid Blue 92 dye from aqueous solutions by single-walled carbon nanotubes: isothermal, kinetic, and thermodynamic studies. Environmental Processes. **8**, 869, **2021**.
95. YADAV V.K., FULEKAR M.H. Biogenic synthesis of maghemite nanoparticles (γ-Fe_2O_3) using Tridax leaf extract and its application for removal of fly ash heavy metals (Pb, Cd). Materials Today: Proceedings. **5**, 20704, **2018**.
96. LIM J., MUJAWAR M., ABDULLAH E., NIZAMUDDIN S., KHALID M., INAMUDDIN. Recent trends in the synthesis of graphene and graphene oxide-based nanomaterials for removal of heavy metals – A review. Journal of Industrial and Engineering Chemistry. **66**, 29, **2018**.
97. SUAREZ-IGLESIAS O., COLLADO S., OULEGO P., DIAZ M. Graphene-family nanomaterials in wastewater treatment plants. Chemical Engineering Journal. **313**, 121, **2017**.
98. SAJID M., PLOTKA-WASYLKA J. Nanoparticles: Synthesis, characteristics, and applications in analytical and other sciences. Microchemical Journal. **154**, 104623, **2020**.
99. URIAN Y.A., ATOCHE-MEDRANO J.J., QUISPE L.T., LEON FELIX L., COAQUIRA J.A.H. Study of the surface properties and particle-particle interactions in oleic acid-coated Fe_3O_4 nanoparticles. Journal of Magnetism and Magnetic Materials. **525**, 167686, **2021**.
100. ZHANG Z., AHMED A.I.S., MALIK M.Z., ALI N., KHAN A., ALI F., HASSAN M.O., MOHAMED B.A., ZDARTA J., BILAL M. Cellulose/inorganic nanoparticles-based nano-bio composite for abatement of water and wastewater pollutants. Chemosphere. **313**, 137483, **2022**.
101. IBRAHIM M.A., JAAFAR M.Z., YUSOF M.A.M., SHYE C.A., SUARDI H., HUSSAIN M.F.M., RAZALI A.Z., IDRIS A.K. The influence of nanoparticle size, concentration, and functionalization on drilling fluid filtration properties. Colloids and Surfaces A: Physicochemical and Engineering Aspects. **693**, 134020, **2024**.
102. MARZUM G., STREICH C., JENDRZEJ S., BARCIKOWSKI S., WAGENER P. Adsorption of colloidal platinum nanoparticles to supports: charge transfer and effects of electrostatic and steric interactions. Langmuir. **30**, 11928, **2014**.
103. YOU J., WANG L., ZHAO Y., BAO W. A review of amino-functionalized magnetic nanoparticles for water treatment: features and prospects. Journal of Cleaner Production. **281**, 124668, **2021**.
104. YU J., WANG A.C., ZHANG M., LIN Z. Water treatment via non-membrane inorganic nanoparticles/cellulose composites. Materials Today. **50**, 329, **2021**.
105. MASUNGA N., MMELESI O.K., KEFENI K.K., MAMBA B. B. Recent advances in copper ferrite nanoparticles and nanocomposites synthesis, magnetic properties and application in water treatment: Review. Journal of Environmental Chemical Engineering. **7** (3), 103179, **2019**.
106. HOLM V.R.A., GREVE M.M., HOLST B. A theoretical investigation of the optical properties of metal nanoparticles in water for photothermal conversion enhancement. Energy Conversion and Management. **149**, 536, **2017**.
107. PUSTOVALOV V.K., ASTAFYEVA L.G., FRITZSCHE W. Analysis of optical properties of spherical metallic nanoparticles for effective absorption of solar radiation and their heating. Solar Energy. **122**, 1334, **2015**.
108. SINGH S., TRIPATHI M.N., PRASAD P.R., SUNIL B.D.Y. Structural, electronic and optical properties of ZnO and TiO2 nanoparticles for wastewater treatment: A first-principles study. Materials Today: Proceedings. **92**, 928, **2023**.
109. HE X., ZHANG K., WANG H., ZHANG Y., XIAO G., NIU H., YAO Y. Tailored carbon-based aramid nanofiber nanocomposites with highly anisotropic thermal conductivity and superior mechanical properties for thermal management. Carbon. **199**, 367, **2022**.
110. ZHOU Y., DONG Z.Y., HSIEH W.P., GONCHAROV A.F., CHEN X.J. Thermal conductivity of materials under pressure. Nature Reviews Physics. **4**, 319, **2022**.
111. GRAY N.F. Microbiology of Waterborne Diseases: Microbiological Aspects and Risks. Second Edition, Elsevier/Academic Press, **2014**.
112. XIAO R., OU T., DING S., FANG C., XU Z., CHU W. Disinfection by-products as environmental contaminants of emerging concern: a review on their occurrence, fate and removal in the urban water cycle. Critical Reviews in Environmental Science and Technology. **53**, 19, **2023**.
113. YOUNAS F., MUSTAFA A., FAROOQI Z.U.R., WANG X., YOUNAS S., MOHYUDDIN W., HAMEED M. A., ABRAR M.M., MAITLO A.A., NOREEN S., HUSSAIN M.M. A critical review of point-of-use drinking water treatment in the United States. Clean Water. **13**, 215, **2021**.
114. JURADO-SANCHEZ B., WANG J. Micromotors for environmental applications: a review. Environmental Science Nano. **5**, 1530, **2018**.
115. ARAGAW T.A., AYALEW A.A. Emerging Techniques for Treatment of Toxic Metals from Wastewater. SCRIBD. **2022**.
116. ASUNION M.H., MARIA D.M. Membranes for Water and Wastewater Treatment. Membranes. **11** (4), 295, **2021**.
117. JI K., LIU C., HE H., MAO X., WEI L., WANG H., ZHANG M., SHEN Y., SUN R., ZHOU F. Research progress of water treatment technology based on nanofiber membranes. Polymers (Basel). **15** (3), 741, **2023**.
118. ESFAHANI M.R., AKTIJ S.A., DABAGHIAN Z., FIROUZIJAEI M.D., RAHIMPOUR A., EKE J., ESCOBAR I.C., ABOLHASSANI M., GREENLEE L. F., ESFAHANI A.R., SADMANI A., KOUTAHZADEH N. Nanocomposite membranes for water separation and purification: Fabrication, modification, and applications. Separation and Purification Technology. **213**, 465, **2019**.
119. MAHMOUD A.E.D., MOSTAFA E. Nanofiltration membranes for the removal of heavy metals from

aqueous solutions: preparations and applications. Membranes (Basel). **13** (9), 789, **2023**.
120. DAS P., GHOSH S., GHOSH R., DAM S., BASKEY M. Madhuca longifolia plant-mediated green synthesis of cupric oxide nanoparticles: A promising environmentally sustainable material for wastewater treatment and efficient antibacterial agent. Journal of Photochemistry and Photobiology B: Biology. **189**, 66, **2018**.
121. YAMAKATA A., VEQUIZO J.J.M. Curious behaviors of photogenerated electrons and holes at the defects on anatase, rutile, and brookite TiO2 powders: A review. Journal of Photochemistry and Photobiology C: Photochemistry Reviews. **40**, 234, **2019**.
122. REN G., HAN H., WANG Y., LIU S., ZHAO J., MENG X., LI Z. Recent advances of photocatalytic application in water treatment: A review. Nanomaterials. **11**, 1804, **2021**.
123. VOISIN H., BERGSTROM L., LIU P., MATHEW A.P. Nanocellulose-based materials for water purification. Nanomaterials. **7** (3), 57, **2017**.
124. AL-RAWAJFEH A.E., ALRAWASHDEH A.I., ETIWI M.T., ALNAWAISEH A., SHAHID M.K., MASAD M.H.M., ORAN S.O., ALSHAHATEET S.F. Silver nanoparticles (Ag-NPs) embedded in zeolite framework: A comprehensive study on bromide removal from water, including characterization, antibacterial properties, and adsorption mechanisms. Desalination Water Treatment. **317**, 100139, **2024**.
125. SHAHID M.K., KASHIF A., FUWAD A., CHOI Y. Current advances in treatment technologies for removal of emerging contaminants from water – A critical review. Coordination Chemistry Reviews. **442**, 213993, **2021**.
126. AL-HARBY N.F., ALBHLY E.F., MOHAMED N.A. Synthesis and Characterization of Novel Uracil-Modified Chitosan as a Promising Adsorbent for Efficient Removal of Congo Red Dye. Polymers (Basel). **14** (2), 271, **2022**.
127. RAY P.C., YU H., FU P.P. Toxicity and Environmental Risks of Nanomaterials: Challenges and Future Needs. Journal of Environmental Science and Health, Part C: Toxicology and Carcinogenesis. **27** (1), 1, **2009**.
128. LEE K.J., NALLATHAMBY P.D., BROWNING L.M., OSGOOD C.J., NANCY XU X.H. In Vivo Imaging of Transport and Biocompatibility of Single Silver Nanoparticles in Early Development of Zebrafish Embryos. ACS Nano. **1** (2), 133, **2007**.