International Journal of
Nanoscience and Nanotechnology

Review Article

2025, Volume 21, Issue 2

# Nanotechnology in Wastewater Treatment: Innovations for a Sustainable Future - A Review

**Dalila Ziani[1*], Aziz Maaliou[1], Leila Djekoune[2], Abderzak Moussouni[3]**

Received 04 March 2025
Accepted 20 May 2025

DOI: 10.22034/ijnn.2026.2054339.2637

International Journal of Nanoscience and Nanotechnology

**Abstract**

This review examines recent advances in nanotechnology for wastewater treatment, with a particular focus on the effectiveness of nanomaterials such as carbon nanotubes, metal nanoparticles, and nanostructured membranes in the adsorption and degradation of pollutants. Research indicates that these materials outperform conventional techniques by enhancing removal efficiency, reducing energy consumption, and minimizing the formation of harmful by-products. Existing studies have primarily focused on characterizing the physicochemical properties of these nanomaterials and evaluating their performance across various wastewater treatment applications. Despite the promising potential of nanotechnology for sustainable water purification, further research is required to assess its long-term environmental impacts and safety prior to large-scale implementation.

**Keywords:** Adsorption; Nanoparticles; Nanostructured Membranes; Nanotechnology; Wastewater Treatment; Water Purification

**How to cite this article**

*Ziani D, Maaliou A, Djekoune L, Moussouni A. Nanotechnology in Wastewater Treatment: Innovations for a Sustainable Future - A Review. Int. J. Nanosci. Nanotechnol., 2025;2: 109-121. DOI:* 10.22034/ijnn.2026.2054339.2637

## 1. Introduction

Water contamination resulting from industrialization and population growth poses a serious global challenge. Wastewater contains heavy metals and various pollutants that threaten human health and ecosystems (Gupta and Tamrakar, 2020). Given that only 2.5–3% of the Earth's water is freshwater and most of it is inaccessible, the development of efficient treatment methods is crucial (Epelle *et al.*, 2022).

Nanotechnology, defined as the manipulation of materials at the atomic scale, has emerged as a promising solution due to its high reactivity and a large specific surface area (Saliby *et al.*, 1999). Unlike conventional treatment methods, which are energy-intensive and often ineffective against micropollutants (Sangalang, 2022), nanomaterials such as carbon nanotubes and graphene-based membranes can efficiently remove contaminants (Kanchi, 2014) . Metallic nanoparticles further enhance filtration and degradation processes while reducing the formation of toxic by-products (MacHado *et al.*, 2019).

Nevertheless, concerns remain regarding the accumulation of nanoparticles in ecosystem, indicating that further research is required to ensure safe application (Lead *et al.*, 2018). Although nanotechnology represents a significant advancement, its potential negative environmental impacts must be carefully evaluated (MacHado *et al.*, 2019).

## 2. Current technologies and limits of wastewater treatment stages

Conventional wastewater treatment typically involves preliminary (screening, sedimentation), primary (coagulation, clarification), secondary (biodegradation), and tertiary (adsorption, reverse osmosis) processes. However, these methods are often energy-intensive and fail to completely remove emerging contaminants. Nanotechnology-based approaches, particularly photocatalysis, offer an efficient alternative for enhancing pollutant removal and overall treatment performance (Epelle *et al.*, 2022).

## 3. Nanotechnology for Contaminant Removal

### 3.1. Overview of nanotechnology

Nanotechnology, which involves materials with dimensions ranging from 1 to 100 nm, enhances wastewater treatment through the use of nano-adsorbents with high surface areas. As illustrated in Figure 1, nanomaterials

*[1] University of Science and Technology Houari Boumediene, Faculty of Civil Engineering, Department of Geotechnics and Hydraulics, Laboratory of Geotechnical and Hydrological Environment (LEGHYD); PB 32, El-Alia-Bab-Ezzouar, Algiers, 16111, Algeria*

*[2] University of Science and Technology Houari Boumediene, Faculty of Mechanical and Process Engineering, Department of Environmental Engineering, Laboratory of Industrial Process Engineering Sciences (LSGPI); BP 32, El-Alia-Bab-Ezzouar, Algiers, 16111, Algeria*

*[3] University Center Abdelhafid Boussouf Mila, Institute of Science and Technology, Department of Civil Engineering and Hydraulics, Laboratory of Geotechnical and Hydrological Environment (LEGHYD); BP 26 RP, Mila, 43000, Algeria*

*E-mail: dalila.ziani@usthb.edu.dz*

(1-100 nm) are comparable in size to many biological entities (e.g., glucose, antibodies, viruses, and bacteria), which helps explain their unique surface-driven properties and reactivity (Amin, Alazba and Manzoor, 2014). These adsorbents enable efficient contaminant removal without the generation of toxic by-products (Gupta and Tamrakar, 2020). Their high surface-to-volume ratio increases adsorption capacity and catalytic reactivity, making nanomaterials such as magnetic nanoparticles, carbon nanotubes, and iron zeolites effective in removing heavy metals (Agarwal and Goyal, 2023).

Nanostructured titanium oxide membranes employ photocatalysis to degrade organic pollutants and eliminate pathogens, offering particular benefits in regions lacking adequate water infrastructure (Gupta and Tamrakar, 2020). Carbon nanotubes and dendrimers further enhance filtration efficiency by accelerating treatment processes while reducing the formulation of harmful by-products (MacHado *et al.*, 2019).

In addition, the application of nanoparticles in groundwater enables in situ purification, thereby improving the performance of the treatment system (Agarwal and Goyal, 2023).

Overall, nanotechnology optimizes adsorption, catalysis, and material regeneration, providing a sustainable approach to addressing global water treatment challenges (MacHado *et al.*, 2019; Gupta and Tamrakar, 2020; Agarwal and Goyal, 2023).

### 3.2. Scientific and technological advances: Nanomaterial-based materials and applications in wastewater treatment

Nanomaterials possess unique properties that are closely linked to their size, particularly their large specific surface area, which promotes rapid dissolution, enhanced reactivity, and high adsorption capacity. They also exhibit distinctive characteristics such as superparamagnetism, localized surface plasmon resonance, and quantum confinement. These properties enable the development of advanced materials that optimize water and wastewater treatment processes, including membranes, adsorbents, nanocatalysts, functionalized surfaces, coatings, and reagents. Table 1 summarizes the main classes of nanomaterials used in water and wastewater treatment, along with their typical applications and potential limitations (Babatunde *et al.*, 2020)

#### 3.2.1. Adsorption and biosorption

Adsorption refers to the binding of molecules to a solid surface. Owing to their high surface area, nano-adsorbents outperform traditional materials such as activated carbon in the removal of both organic and inorganic pollutants, including heavy metals (Gehrke, Geiser and Somborn-Schulz, 2015). This enhanced efficiency enables the development of faster and more compact water treatment systems, particularly suited to decentralized applications.

Table 2 presents specific pollutant targets, measured adsorption capacities, and each material's advantages and limitations.

Biosorption employs biological materials such bacteria, algae, fungi as natural adsorbents to bind and remove heavy metals, even at low concentrations. This process is based on mechanisms including micro-precipitation, ion exchange, and complexation at the cell surface or through metabolic pathways involving ATP (Jain, Patel and Pardhi, 2021).

**Table 1.** Nanomaterials and their application in water treatment.

| Nanomaterials | | Application | Probable limitations |
|---|---|---|---|
| Nano-adsorbents | ·Carbon nanotubes (CNTs) | Removal of heavy metals and various organic contaminants from wastewater | Secondary pollution may arise due to difficulties in separating nanoparticles from aqueous solution because of their small particle size. |
| | ·Graphene-based nano-adsorbent | Adsorption of heavy metals present in wastewater | |
| | ·Polymeric nano-adsorbents | Removal of organic compounds and heavy metals<br>Removal of anionic compounds such as dye | Challenge related to economic reuse and regeneration |
| | ·Zeolites | Disinfection of water<br>Hybrid forms remove heavy metals such as nickel and lead from wastewater | |
| | ·Oxide-based nanoparticles | Removal of hazardous pollutants<br>Adsorption of heavy metals | |
| Nanomembranes | | Reduction of hardness, color, odor, and heavy metal ions from groundwater | The life cycle of some nanomembrane may contribute more to toxicity, global warming and ozone depletion than traditional materials |
| Nanocatalysts | | Low-pressure desalination of seawater<br>Effective elimination of dyes and heavy metals<br>Photocatalytic, electrocatalytic and catalytic<br>Degradation of microbial contaminants in purification of water | Increased likelihood of membrane fouling<br>At the industrial level, the need for UV radiation for photocatalytic activity may predispose workers to skin cancers and DNA mutation<br>Fenton-catalysts are associated with continuous catalyst loss and require acidic conditions for optimal performance |

**Table 2.** Comparison of nanomaterial performance in wastewater treatment (adsorption).

| Type of Nanomaterial | Target Pollutants | Adsorption Capacity (mg $g^{-1}$) | Experimental Conditions | Advantages | Challenges/Limitations | References |
|---|---|---|---|---|---|---|
| modified zeolites | Ammonium Phosphorus Heavy metals | organic dyes (methyl orange, methylene blue) | varies based on modification (up to 400 mg/g for some dyes) | pH 5-7, ambient temperature | low cost, easy to modify | (Shi *et al.*, 2017) |
| magnetic nanoparticles | heavy metals ($Pb^{2+}$, $Cd^{2+}$) | 300-500 mg/g | pH 6-8, moderate stirring | recoverable, highly specific | risk of leaching | (Singh.S, Kosalge and Bhatia, 2024) |
| $CuFe_2O_4$ nanocomposites | cationic/Anionic dyes (CV, RB, CR) | 666.6 mg $g^{-1}$ (CV), 645.16 mg $g^{-1}$ (RB), 434.71 mg $g^{-1}$ (CR) | pH 4-10, temperature 308 K | high capacity, renewable | relatively high synthesis cost | (Dabagh *et al.*, 2024) |
| carbon quantum dots | humic substances | high but dependent on modification | neutral pH, low concentration | simplicity, large active surface area | efficiency dependent on pretreatments | (Pirbavepour *et al.*, 2024) |
| doped graphene | arsenic ($As^{3+}$, $As^{5+}$) | Up to 98% removal under optimal conditions | pH 3-8, slightly acidic environment | compatible with advanced membranes | challenges with industrial integration | (Alomar *et al.*, 2024) |

#### 3.2.1.1. Carbon nanotubes

Carbon nanotubes (CNTs) are nanoscale cylindrical carbon structures classified as single-walled (SWCNTs) or multi-walled (MWCNTs). Figure 2 schematically illustrates the structure of SWCNTs and MWCNTs, highlighting the tubular graphene-based architecture that contributes to their high surface area and enhanced adsorption performance (Parveen, Rana and Fangueiro, 2013; Epelle et al., 2022). Their large surface area and reactive adsorption sites make CNTs highly effective in removing persistent pollutants and metal ions through electrostatic and chemical interactions, and they also exhibit antimicrobial properties (Gehrke, Geiser and Somborn-Schulz, 2015).

Compared with activated carbon and zeolites, CNTs possess superior thermal, mechanical, and chemical properties and can be incorporated into filtration membranes enhance pollutant rejection and overall treatment efficiency. However, high production costs limit their large-scale applications, Nevertheless they remain viable for point-of-use systems targeting pharmaceutical and antibiotic contaminants (Gehrke, Geiser and Somborn-Schulz, 2015).

To address the challenges related to hydrophobicity and aggregation, advanced approaches such as polymer functionalization have been developed, significantly enhancing the adsorption capacity of CNTs for dyes and heavy metals (Essa et al., 2022; Tripathy et al., 2024).

#### 3.2.1.2. Graphene Nanoparticles

Graphene-based nanoparticles (GBNs), including graphene, graphene oxide (GO), and reduced graphene oxide (rGO), exhibit high adsorption capacity for organic pollutants and heavy metals due to their oxygen-containing functional groups and large specific surface area (Epelle *et al.*, 2022). As illustrated in Figure 3, graphene, GO, and rGO differ in their surface chemistry and distribution of oxygenated functional groups, which strongly influence their adsorption and removal behavior. (Jayakaran, Nirmala and Lakshmanarao, 2019). Compared with carbon nanotubes, resins, and activated carbon, GBNs demonstrate superior efficiency in water remediation.

GO is synthesized through the chemical oxidation of graphite, whereas rGO is obtained via chemical reduction. Both materials contain oxygenated functional groups (C-OH, C=O) that enhance pollutant adsorption (Jayakaran, Nirmala and Govindarajan, 2019). GBNs are chemically stable under extreme pH conditions and effectively remove polycyclic aromatic hydrocarbons (PAHs), dyes, and antibiotics (Tripathy *et al.*, 2024).

Studies indicate that GO exhibits superior adsorption of both polar and non-polar compounds, while rGO is more effective for non-polar organics like PAHs (Yang *et al.*, 2018). Environmental factors, particularly pH, significantly influence adsorption performance, with GO adsorption increasing at low pH and rGO at high pH (Peng *et al.*, 2017; Hossain, Akther and Zhou, 2020).

Despite its high efficiency, the large-scale application of GO in wastewater treatment is constrained by high synthesis costs and complex functionalization processes.

#### 3.2.1.3. Fullerenes

Fullerenes, particularly C60 buckminsterfullerene, are spherical nanostructures with high chemical and mechanical stability, making them effective materials for water treatment applications (Bhat *et al.*, 2024).

Functionalization with hydroxyl, carboxyl, or epoxide groups enhances their solubility and interaction with organic and metallic pollutants.

Fullerenes, synthesized via carbon vapor condensation, exhibit photochemical activity that improves UV-assisted disinfection processes (Jasaswini *et al.*, 2024). Their adsorption efficiency is further enhanced when combined with $ZnFe_2O_4$ magnetic nanoparticles, facilitating the removal of heavy metal such as (Hg(II), Cd(II), Sn(II), Pb(II)) as well as enabling adsorbent reuse (Adam *et al.*, 2021).

The impact of fullerenes on microorganisms varies

**Table 3.** Applications of Zeolite Nanoparticles in Wastewater Treatment.

| Zeolite type | Target pollutants | Adsorption capacity (mg/g) | Advantages | Limitations | References |
|---|---|---|---|---|---|
| Zeolites modified with magnetic nanoparticles | Organic dyes (Methylene Blue) | Up to 400 | High ion exchange capacity | High cost of modification | (Majid, AbdulRazak and Noori, 2019) |
| Sodalite zeolites | Direct dyes (DR23 and DR80) | Up to 500 | High specific surface area | Requires advanced modifications | (Mahmoodi and Saffar-Dastgerdi, 2019) |
| Clinoptilolite zeolites | Olive mill wastewater | >80% salinity reduction | Proven efficiency | Efficiency depends on pH | (Aly *et al.*, 2018) |

according to particle size and shape, influencing photosensitivity and bacterial toxicity (Chae *et al.*, 2011). Although some studies report low cytotoxicity, concerns regarding their ecotoxicity persist, necessitating further validation for sustainable application (Moussa *et al.*, 1996; Sayes *et al.*, 2004; Romero-Franco *et al.*, 2017).

#### 3.2.1.4. Polymeric Nano-Adsorbents

Polymeric nano-adsorbents enhance wastewater treatment owing to their high porosity, reactivity, and surface area, which enhance pollutant adsorption efficiency (Kumari, Alam and Siddiqi, 2019). Carbon-based, polymeric, and metal/metal oxide nano-adsorbents, including Ag/polyaniline, Ag/carbon, and $C/TiO_2$, had demonstrated effective removal of organic pollutants and heavy metals (MacHado *et al.*, 2019; Tripathy *et al.*, 2024).

Magnetic nano-sorbents facilitate organic pollutant removal through magnetic filtration and offer regenerability via ion exchange and magnetic forces, reducing operational costs (Tripathy *et al.*, 2024). Dendrimers enable near-complete recovery of copper ions when incorporated into ultrafiltration systems; however, their complex synthesis limits large-scale commercialization. Owing to their branched structures, dendrimers efficiently adsorb organic compounds within hydrophobic cores and bind heavy metals through modified outer branches (Sadeghi-Kiakhani, Arami and Gharanjig, 2013).

Bioadsorbents, such as chitosan-dendrimer nano-structures, provide biodegradable and non-toxic alternatives, achieving up to 99% dye removal from textile wastewater (Sadeghi-Kiakhani, Arami and Gharanjig, 2013). Nevertheless, concerns regarding potential health effects associated with exposure to carbon-based nanomaterials have driven the search for alternatives with lower environmental and health risks (Tripathy *et al.*, 2024).

### 3.2.2. Zeolite Nanoparticles

Zeolites are porous crystalline aluminosilicates that efficiently remove contaminants through cation exchange mechanisms, particularly in water disinfection involving silver ion incorporation (Petrik *et al.*, 2012). nano- zeolites, synthesized using laser fragmentation techniques, further enhance wastewater treatment efficiency (Dhermendra *et al.*, 2008).

The integration of zeolites with carbon nanotubes (CNTs) and nano-metals improves heavy metal removal performance, however, high costs and filtration requirements limit the widespread adoption of CNT-based systems (Gehrke, Geiser and Somborn-Schulz, 2015). Zeolites also act as catalysts in chemical processes, facilitating reactions through their porous structure (Umejuru et al., 2023).

Both natural and synthetic zeolites, including clinoptilolite, zeolite 4A, and zeolite X, are widely applied for heavy metal adsorption, with synthetic variants generally exhibiting higher efficiency (Vishnu *et al.*, 2021; Gao *et al.*, 2022; Jarosz *et al.*, 2022). The incorporation of NaX zeolite nanoparticles into polysulfone membranes has been shown to significantly enhance lead and nickel removal (Yurekli, 2016).

Table 3 presents a selection of studies that illustrate the performance of different types of zeolite nanoparticles used in wastewater treatment.

### 3.2.3. Nano-metals and Nano-metal Oxides

Nano-metals and nano-metal oxides are highly effective materials for the removal of harmful metals and radionuclides from water. Their high surface area facilitates rapid diffusion across the structure, and their excellent structural stability allows for efficient industrial application. Certain oxides, such as nano maghemite and nano magnetite, exhibit superparamagnetic properties, enabling efficient separation and recovery, thereby reducing operational costs and material waste (Tahoon *et al.*, 2020).

Iron nanohydroxide ($\alpha$-FeO(OH)), with its large surface area, selectively adsorbs arsenic, making it valuable for both drinking water and wastewater treatment (Hao *et al.*, 2018). Hybrid materials, such as ArsenXnp, which incorporate iron oxide nanoparticles into ion-exchange polymers, further enhance arsenic removal efficiency, while reducing water consumption and operational costs (Ashraf *et al.*, 2019).

The integration of nanotechnology with composite materials and polymers continues to improve pollutant removal efficiency; however, high costs and recyclability challenges require further research for large-scale implementation.

Table 4 summarizes recent studies on nano-metals and metal oxides used in wastewater treatment, highlighting target pollutants, adsorption capacity, main applications, and associated challenges.

**Table 4.** Nano-metals and Metal Oxides in Wastewater Treatment.

| Type of nano-metal | Target pollutants | Adsorption capacity (mg $g^{-1}$) | Main applications | Challenges | References |
|---|---|---|---|---|---|
| Iron nanoparticles ($Fe^{2+}$) | arsenic, nitrates | 100-300 | contaminated water treatment | prone to rapid oxidation | (Saini and Bhatia, 2024) |
| Zinc oxides (ZnO) | organic dyes, bacteria | 200-400 | antibacterial properties | environmental toxicity | (Dabagh *et al.*, 2024) |
| Iron oxides ($Fe_2O_3$, $Fe_3O_4$) | heavy metals, dyes | 300-500 | magnetic recovery | high synthesis cost | (Pirbavepour *et al.*, 2024) |

**Table 5.** Examples of silver nanoparticles in wastewater treatment.

| Nanoparticles properties | Specific applications | Efficiency | Advantages | Limitations | References |
|---|---|---|---|---|---|
| Pure silver nanoparticles | Dye removal, organic pollutant degradation | High efficiency in dye degradation | Antimicrobial properties, high surface-to-volume ratio | Potential environmental impact | (Palani *et al.*, 2023) |
| Silver nanoparticles (AgNPs) | Wastewater disinfection | Effective against pathogens | Low cost, versatile synthesis | Risk of accumulation in biosolids | (Maharana and Acharya, 2024) |
| Silver nanoparticles (Green synthesis) | Wastewater treatment using plant extracts | High antimicrobial activity, effective in pollutant degradation | Eco-friendly synthesis, cost-effective | Variability in nanoparticle characteristics | (Vanlalveni *et al.*, 2021) |

**3.2.4. Silver Nanoparticles**

Silver nanoparticles (AgNPs) exhibit strong antimicrobial properties. They effectively disinfect water by targeting pathogens like *Escherichia coli* with minimal toxicity to animal cells (Baker *et al.*, 2005). Their bactericidal activity is influenced by particle size and shape, with smaller particles (~8 nm) and truncated triangular nanoplatelets demonstrating the highest efficacy (Amin, Alazba and Manzoor, 2014).

AgNPs eliminate bacteria through mechanisms including free radical generation, DNA interaction, and membrane adhesion, reducing the risk of antibiotic resistance development (Liau *et al.*, 1997; Danilczuk *et al.*, 2006; Kim *et al.*, 2007). Applications include silver-coated polyurethane foam filters and silver-based nanocatalysts, which effectively degrade microbial contaminants (Jain and Pradeep, 2005; Chaturvedi, Dave and Shah, 2012). However, their long-term efficiency declines due to silver ion depletion, leading researchers to explore AgNP-metal oxide composites for improved durability.

AgNPs are synthesized using methods such as inert gas condensation (IGC), co-condensation, chemical reduction, and UV photo-reduction, with smaller particles exhibiting enhanced antimicrobial efficiency (Iravani *et al.*, 2014) . Hybrid approaches that integrate AgNPs with polymers or Schiff bases further improve metal ion removal and antifungal performance (Tripathy *et al.*, 2024). These advancements underscore the potential of AgNPs as effective agents in advanced wastewater treatment.

The properties, applications, and limitations of silver nanoparticles used in wastewater treatment are highlighted in Table 5.

**3.2.5. Nanoscale titanium dioxide**

Nanoscale titanium dioxide ($TiO_2$) is widely recognized as a photocatalyst in photosynthesis due to its strong chemical stability, low toxicity, and cost-effectiveness (Jasaswini *et al.*, 2024). At the nanoscale, increased surface area and porosity enhance adsorption efficiency for heavy metals such as (Pb(II), Ni(II), Zn(II), Cd(II), Cu(II)), while the availability of exposed active sites improves contaminant degradation (Khoshkerdar and Esmaeili, 2019).

Under UV light irradiation, $TiO_2$ generates hydroxyl radicals that effectively that mineralize organic pollutants and eliminate microorganisms, including bacteria, fungi, and protozoa (Jasaswini *et al.*, 2024). Structural modifications, such as $Ti^{3+}$ incorporation, further enhance catalytic properties and light absorption (Xiong *et al.*, 2012).

Hybrid $TiO_2$-based composites, combined with polymers or semiconductors, offer improved recyclability and performance (Nasr *et al.*, 2021). $TiO_2$ exhibits exceptional durability and long-term decontamination efficiency, although UV activation is required, in contrast to nano-silver, which gradually loses activity over time (Liu and Chen, 2014).

Table 6 provides a selection of studies that demonstrate the efficacy of nanoscale $TiO_2$-based materials in wastewater treatment.

**3.2.6. Magnetic Nanoparticles**

Magnetic nanoparticles, primarily magnetite ($Fe_3O_4$), are highly effective for groundwater remediation, particularly for the removal of pollutants such as arsenic. Unlike conventional methods, these particles enable in situ intervention, interacting directly with contaminants and allowing recovery via magnetic field thereby reducing operational costs and environmental impact (Gutierrez, Dziubla and Hilt, 2017). In addition to groundwater remediation, they are applied in filtration and coagulation processes, enhancing contaminant removal from water (Mohamed Noor *et al.*, 2022). Their incorporation into direct osmosis systems also optimizes osmotic pressure and overall performance (Shukla, Khan and Daverey, 2021).

**Table 6.** Examples of titanium dioxide nano-materials in wastewater treatment.

| Type of $TiO_2$ material | Target pollutants | Efficiency (%) | Advantages | Limitations | References |
|---|---|---|---|---|---|
| $TiO_2$ nanoparticles with graphene | Organic pollutants, industrial dyes | ~93% | Enhanced photocatalytic activity | Complex synthesis process | (Qasim *et al.*, 2024) |
| $TiO_2$-alginate composites | Reactive Black-5 (textile dye) | ~95% | Easy immobilization | Dependency on UV light | (Lam, Tee and Ban, 2024) |

**Table 7.** Examples of magnetic nanoparticles in wastewater treatment.

| Type of magnetic nanoparticle | Target pollutants | Efficiency (%) | Advantages | Limitations | References |
|---|---|---|---|---|---|
| Spinel ferrites ($CoFe_2O_4$, $NiFe_2O_4$) | Heavy metals, organic pollutants | ~90% | High magnetic recovery | Sensitive to environmental pH | (Akbar, Bhavani Lakshmi and Ghosha, 2024) |
| nano-composites $ZnO/NiFe_2O_4$ | Organic dyes | ~88% | Cost-effective and green synthesis | Requires optimization for industrial use | (Tijani *et al.*, 2020) |

Magnetic nanoparticles can be efficiently recovered by magnetic separation, preventing their dispersion and minimizing environmental damage. They are also combined with hybrid materials such as polymers or membranes to improve stability and reusability, making them a suitable for continuous wastewater treatment (Mohammed *et al.*, 2017).

Although primarily explored in medical applications, further studies on toxicology and environmental impact are essential to ensure safe implantation in water treatment (Gutierrez, Dziubla and Hilt, 2017). Additionally, they are capable of removing organic pollutants, including polycyclic aromatic hydrocarbons and dyes, thereby enhancing environmental remediation (Shukla, Khan and Daverey, 2021).

Table 7 shows some studies that have examined the properties, applications, and disadvantages of magnetic nanoparticles in wastewater treatment.

#### 3.2.7. Nanovalent zero iron

Nanovalent zero iron (nZVI) is a critical technology in wastewater treatment, particularly for the decontamination of groundwater from chlorinated organic compounds, heavy metals, and persistent pollutants. Its high surface area facilitates efficient in situ remediation, eliminating the need for surface water pumping and reducing operational costs and environmental impact (Zhao *et al.*, 2016). Zero-valent iron emulsions (EZVI) enhance nZVI's capacity to treat dense non-aqueous phase liquids (DNAPL) and chlorinated hydrocarbons, converting them into harmless products (Galdames *et al.*, 2020). However, high reactivity of nZVI can lead to oxidation and passivation, reducing its effective lifespan. The use of stabilizers mitigates aggregation and improves mobility, extending effectiveness (Pandey, Sharma and Saha, 2022).

nZVI has been successfully applied to remove nitrates, arsenic, heavy metals, and industrial leachates, often in hybrid filtration and coagulation systems (Zafar *et al.*, 2021). While cost-effective, concerns regarding the toxicity of by-products necessitate careful monitoring and further research focused on sustainable and environmentally safe implementation (Galdames *et al.*, 2020).

Table 8 provides a synopsis of select studies concerning the applications, efficacy, and limitations of nanovalent zero iron in wastewater treatment.

### 3.3. Membranes and membrane processes

Membranes represent a high-efficiency approach to wastewater treatment by separating pollutants from water with minimal energy consumption. The advent of nanotechnology has significantly enhanced membrane permeability, selectivity, and durability, making nanofiltration (NF) membranes particularly effective for the removal of heavy metals, dyes, and persistent organic compounds from wastewater (Oatley-Radcliffe *et al.*, 2017; Mulyanti and Susanto, 2018). Nanocomposite membranes, which combine polymer matrices with $TiO_2$ or nano-silver nanoparticles, exhibit improved mechanical strength and chemical resistance while reducing fouling due to their antimicrobial and hydrophilic properties. These membranes are especially effective in treating wastewater with high organic loads and biofilm contamination (Abdel-Fatah, 2018).

Nanofiber membranes, produced by electrospinning, offer high porosity and excellent contaminant retention. Functionalization with nanoparticles further enhances their ability to remove bacteria and organic pollutants (Agboola *et al.*, 2015). Inspired by aquaporins, biomimetic membranes demonstrate exceptional water permeability and selectivity, though challenges in large-scale manufacturing remain (Mohammad *et al.*, 2015).

Photocatalytic coatings incorporating $TiO_2$ or silver nanoparticles improve membrane durability by reducing fouling and enabling self-cleaning mechanisms, thereby lowering operational costs (Zhang *et al.*, 2021).

Despite these advances, challenges remain regarding production costs, long-term durability, and the potential release of residual nanoparticles into wastewater, which require ongoing investigation for broader implementation in wastewater treatment.

Table 9 exemplifies the studies that emphasize nanocomposite membrane performance and challenges in wastewater treatment.

### 3.4. Photocatalysis

Photocatalysis is an emerging technology in wastewater treatment that addresses various issues such

**Table 8.** Examples of zero-valent iron nanoparticles in wastewater treatment.

| Type of nZVI material | Target pollutants | Efficiency (%) | Advantages | Limitations | References |
|---|---|---|---|---|---|
| nZVI particles ($Fe^0$) | Zinc ions ($Zn^{2+}$) | ~90% | High reactivity | Potential aggregation in water | (Liang *et al.*, 2014) |
| nZVI for textile dyes | Methylene blue | ~85-90% | Cost-effective, scalable | Toxicity at high concentrations | (Hamdy, Mostafa and Nasr, 2018) |
| Modified nZVI | Organic and inorganic pollutants | ~95% | Broad pollutant range | Requires surface modification | (Pasinszki and Krebsz, 2020) |

**Table 9.** Examples of nano-composite membranes for wastewater treatment.

| Type of membrane | Pollutants removed | Efficiency (%) | Advantages | Challenges | References |
|---|---|---|---|---|---|
| PVDF-based nano-composite membranes | Heavy metals, organic dyes | 85-95% | High stability, selective removal | High production cost | (Salim *et al.*, 2019) |
| Polymeric nano-composite membranes | Pharmaceuticals, microplastics | 90-98% | Broad application range | Scalability issues | (Zahid *et al.*, 2018) |
| Graphene oxide-enhanced membranes | Pathogens, VOCs (Volatile Organic Compounds) | ~95% | Enhanced permeability | Complex fabrication process | (Ursino *et al.*, 2018) |

as eliminating organic micro-pollutants or the associated disinfecting process. It operates by illuminating photocatalytic materials like titanium dioxide ($TiO_2$), with UV light, generating electron-hole pairs that produce reactive radicals capable of decomposing pollutants into harmless byproducts (Majid Mohadesi and Shokri, 2024).

However, conventional photocatalysis is limited by low UV light availability in the solar spectrum, making it inefficient for industrial use. Innovations including metal-doped $TiO_2$ and nanocomposites development have extended $TiO_2$ activation to visible light, substantially enhancing its industrial potential (Horikoshi and Serpone, 2020).

Photocatalytic membrane reactors integrate photocatalysis with membrane filtration, improving pollutant removal while retaining nanoparticles to prevent environmental release. Membranes incorporating $TiO_2$ or nanosilver exhibit high effectiveness in treating micro-pollutants and reducing fouling (Al-Mamun *et al.*, 2019).

Practical applications in textile and pharmaceutical wastewater treatment have shown high degradation rates for complex pollutants with low energy consumption (Kanakaraju, Glass and Oelgemöller, 2014). Coupled solar photocatalytic systems with membrane filtration have also been successfully employed to reduce both organic and inorganic pollutants (Zhang, Wang and Zhang, 2014).

Despite these advancements, challenges such as production costs, durability, and large-scale deployment continue to limit widespread adoption. Ongoing research focuses on enhancing photonic efficiency and minimizing electron-hole recombination, providing opportunities to overcome these obstacles and advance the practical implementation of photocatalytic technologies.

Table 10 shows examples of studies on photocatalysts and their performance in wastewater treatment.

### 3.5. Emerging Nanotechnologies and Perspectives

Advanced nanotechnologies are transforming the wastewater treatment sector by offering innovative approaches to remove toxic chemicals from the wastewater of numerous types of pollutants and maintain ecosystem health. Nano-adsorbents, including metal oxide nanoparticles and carbon-based composites, effectively eliminate heavy metals, organic micro-pollutants, and dyes from industrial wastewater. These materials outperform conventional methods in adsorption capacity and recyclability while reducing operational costs (Jiang *et al.*, 2018).

Nanotechnology membranes incorporating nanofibers or antimicrobial nanoparticles offer enhanced pollutants filtration and degradation. Hybrid systems combining membranes and photocatalysis have proven effective in treating highly contaminated water while minimizing the environmental release of nanomaterials (Jain *et al.*, 2021).

Innovations like doped nanoparticles and broad spectrum catalysts enable operation under visible light, facilitating low-energy applications, particularly beneficial for developing countries facing energy constraints and water scarcity (Brame, Li and Alvarez, 2011).

Concerns regarding the ecological impacts of nanomaterials, especially their interactions with aquatic systems, underscore the necessity of stringent regulatory frameworks to mitigate adverse effects while preserving microbial benefits (J. Theron and Cloete, 2008). Integrating nanotechnology with artificial intelligence and circular economy principles offers opportunities to optimize manufacturing, reduce costs, and establish regulatory guidelines for broader adoption in wastewater treatment (Adegoke *et al.*, 2023).

Table 11 presents some new nanotechnologies, detailing their applications, benefits, and challenges in wastewater treatment. It details how they are used, their benefits, and their challenges in wastewater treatment.

### 3.6. Environmental Impact and Management of Nanomaterials

Innovations in nanotechnology are bringing significant changes in the wastewater treatment sector, introducing advanced pollutant removal methods.

Despite the increasing application of nanomaterials in wastewater treatment, their application raises environmental and health concerns, particularly regarding their environmental fate and potential toxicity to aquatic organisms. Due to their small size and high chemical

**Table 10.** Examples of photocatalysts in wastewater treatment.

| Type of photocatalyst | Target pollutants | Efficiency (%) | Advantages | Limitations | References |
|---|---|---|---|---|---|
| Nano-fibrous photocatalytic membranes ($TiO_2$-Electrospun) | Organic pollutants, dyes | ~92% | High surface area | Fabrication cost | (Nasir *et al.*, 2021) |
| $ZnO/TiO_2/H_2O_2$ composites | Anthracene, PAHs | ~85-92% | Enhanced degradation speed | Dependent on specific conditions | (Marzoq *et al.*, 2024) |
| $TiO_2$-alginate composites ($TiO_2$/Alginate) | Reactive black-5 (textile dye) | ~95% | Easy immobilization | Dependent on UV light | (Lam, Tee and Ban, 2024) |

**Table 11.** Examples of emerging nano-technologies and their future perspectives.

| Nanotechnology | Emerging applications | Advantages | Challenges | References |
|---|---|---|---|---|
| Spinel ferrite core-shell nanostructures ($Fe_3O_4/TiO_2$) | Heavy metal removal, catalysis | High stability and reusability | Synthesis complexity | (Kurian and Thankachan, 2021) |
| Functionalized nanoparticles | Removal of emerging contaminants | Enhanced specificity | Environmental persistence | (Patel, Pinos-Vélez and Cipriani-Avila, 2024) |

**Table 12.** Environmental impact and management of nanomaterials.

| Nanomaterial | Environmental risks | Management strategies | Advantages | Challenges | References |
|---|---|---|---|---|---|
| Metal-based nanoparticles | Bioaccumulation in aquatic systems | Recovery and recycling | High remediation efficiency | Potential toxicity to flora and fauna | (Anwar *et al.*, 2024) |
| Functionalized nanoparticles | Persistent in the environment | Surface functionalization | Enhanced pollutant adsorption | High modification costs | (Patel, Pinos-Vélez and Cipriani-Avila, 2024) |
| Carbon nano-tubes | Long degradation times | Development of biodegradable alternatives | High adsorption capacity | Bioaccumulation concerns | (Rafieenia *et al.*, 2024) |

reactivity, nanoparticles can interact with aquatic organisms, leading to bioaccumulation and potential toxic effects (Jain *et al.*, 2021). Uncontrolled release of nanoparticles from wastewater treatment plant effluents represents a major environmental challenge requiring urgent attention from both the scientific community and policymakers.

The potential risks of nanoparticles arise from their persistence in environmental systems, where they are difficult to remove, their ability to cross biological membranes, and may induce cellular damage. For instance, metallic nanoparticles such as silver and titanium dioxide ($TiO_2$) can generate reactive oxygen species (ROS), causing oxidative damage in aquatic life (Saleem and Zaidi, 2020). Additionally, nanoparticles can increase the mobility and bioavailability of pollutants in natural systems (Babatunde *et al.*, 2020).

Effective management strategies include nanofiltration and modified membranes to capture nanoparticles during treatment. Immobilizing nanoparticles on solid substrates (e.g., ceramic membranes) reduces environmental release while preserving catalytic activity (Jiang *et al.*, 2018).

Life cycle assessment has emerged as a crucial tool for estimating the environmental burden of nanomaterials, highlighting challenges such as energy consumption during production and nanoparticle waste disposal (Bystrzejewska-Piotrowska, Golimowski and Urban, 2009). Regulatory frameworks that ensure product safety, integrate toxicity evaluation, and enforce proper waste management are essential for sustainable nanomaterial use in water treatment.

Further development should focus on biodegradable or recyclable nanomaterials to minimize environmental impact. Concurrently, continued research is needed to assess toxicity in aquatic ecosystems and the potential contribution of nanomaterials to the proliferation of antibiotic-resistant bacteria.

Table 12 highlights nano-materials, their environmental risks, and management strategies.

### 3.7. Case Studies: Applications in Industry and Municipalities

Nanotechnology is revolutionizing wastewater treatment in both industrial and municipal contexts, enabling the removal of complex contaminants while reducing energy consumption. Metal oxide nanoparticles including doped $TiO_2$ and nano-silver efficiently eliminate pollutants, while nanocatalyst-functionalized membranes enhance the removal of heavy metals and organic compounds (Sikiru et al., 2022).

In Mexico City, zeolite-iron nanoparticle nanocomposites successfully treated domestic wastewater, reducing contaminant levels and maintenance costs (Olvera *et al.*, 2017). In Brazil, nanosensors optimize filtration by monitoring and adjusting pollutant concentrations in real time (Kamali *et al.*, 2019). Magnetic nanoparticles have been applied in mining wastewater treatment, effectively removing metals like lead and arsenic, enabling easy recovery and lowering operational costs (Garcia-Segura *et al.*, 2020).

**Table 13.** Case studies: industrial and municipal applications.

| Case Study | Technology used | Pollutants treated | Results | Challenges | References |
|---|---|---|---|---|---|
| Municipal wastewater remediation | Nano-materials and bio-based filters | Pathogens, organic pollutants | Up to 90% removal efficiency | High initial cost | (Anwar *et al.*, 2024) |
| Industrial effluent treatment | MOFs and nano-fibers | Heavy metals, pharmaceutical residues | 85-92% removal efficiency | Scalability challenges | (Zamel *et al.*, 2022) |

Despite these technological advancements, high costs and insufficient regulatory frameworks limit widespread adoption. Standardization and policy development are particularly critical for implementation in developing countries.

Table 13 shows case studies, technologies, pollutants, and challenges.

### 3.8. Economics and feasibility

Nanotechnology offer efficient solutions for wastewater management, but high initial costs for materials such as nanocomposite membranes and metal nanoparticles remain a concern. Nevertheless, these technologies can yield long-term savings by reducing chemical consumption, minimizing maintenance, and improving energy efficiency (Mpongwana and Rathilal, 2022). For example, iron/copper nanoparticles reduced textile wastewater treatment costs by 30% while enhancing water quality (Mahmoud, Mostafa and Peters, 2021). Hybrid systems combining membrane filtration and photocatalysis also provide rapid returns on investment due to their energy efficiency (Kamali *et al.*, 2019).

Implementation costs can be prohibitive, particularly in developing countries where standardization is limited. Addressing these barriers requires manufacturing cost-effective nanomaterials and integrating them into the existing treatment systems, supported by robust public policy. Public-private partnerships are essential to facilitate sustainable adoption of nanotechnologies in wastewater treatment (Olvera *et al.*, 2017).

### 3.9. Regulation and Social Acceptance

The widespread application of nanotechnologies in wastewater treatment faces regulatory and societal challenges. Many countries lack established legal frameworks for the use, management, and disposal of nanomaterials, which hinders regulatory approval, especially in developing regions (Falinski *et al.*, 2020).

Currently, no standardized guidelines systematically address the toxicity of nanomaterials and their possible long-term environmental impacts, making effective regulation difficult. Research aims to inform regulations based on validated toxicological studies to ensure the safe application of nanomaterials (Babatunde *et al.*, 2020). Social acceptance is equally important as communities may be hesitant to adopt nanotechnologies without adequate awareness. For instance, in South Africa, public outreach and transparency improved acceptance of nano-activated wastewater treatment technologies (Gxaba, 2019).

Addressing these problems would be easier if clear policies aligned with international standards were established. Clear international policies, collaboration among scientists, regulators, and stakeholders, and public-private engagement are crucial for aligning conventional approaches with nanotechnologies Such cooperation facilitates investment, infrastructure development, and public policy support, promoting broader adoption in smart and sustainable urban systems (Singh *et al.*, 2024).

### 3.10. Future Prospects and Current Research

Advancements in nanotechnology for water purification focus on enhancing efficiency, reducing costs, and minimizing environmental impact. Current research emphasizes the development of biodegradable and recyclable materials, including nano-sized particles designed to address pollution while minimizing harm to ecosystems.

Functionalized nanomaterials, including doped nanoparticles and hybrid nanocomposites, integrate adsorption, catalysis, and decontamination within a single process. For example, carbon nanotubes doped with rare metals are being explored for targeted contaminant removal with low energy input (Bhat *et al.*, 2022).

Artificial intelligence (AI) and machine learning can complement nanotechnology by enabling real-time monitoring and site-specific treatment optimization, according to Sahu *et al.* (2021).

Nevertheless, challenges remain, including the need for standardizing production methods, and a comprehensive understanding of the long-term toxicity of nanomaterials.

Global cooperation is essential to establish harmonized policies, training programs and responsible implementation strategies (Kamali *et al.*, 2019).

Ongoing research investigates sustainable approaches such as hybrid reactors combining solar photocatalysis with nanostructured membranes, offering potential benefits for rural and developing regions (Jain, Patel and Pardhi, 2021).

Overall, nanotechnology represents a promising future for wastewater treatment, with sustainability, AI integration, and hybrid systems serving as key drivers to improve efficiency, cost-effectiveness, and environmental performance.

## 4. Conclusion

Nanotechnologies offer groundbreaking solutions in wastewater management, addressing emerging contaminants and environmental challenges. This review emphasizes their applications in adsorbent nanoparticles, nanocomposite membranes, photocatalysis, and functionalized nanomaterials, which enhance treatment efficiency, target complex contaminants, and enable more sustainable and cost-effective approaches to conventional methods.

While nanocomposite membranes improve filtration efficiency and operational cost-effectiveness, their toxicity and environmental persistence remain significant challenges. High upfront costs, as well as the lack of regulation, are factors that have limited widespread adoption, particularly in developing countries. Overcoming these requires robust research programs, coordinated public-private partnerships, and balanced understanding of both the benefits and risks associated with nano-materials.

Despite existing challenges, nanotechnologies demonstrate considerable promise for wastewater treatment, particularly in removing organic (micro) pollutants, antibiotics, and heavy metals, thereby showing their potential for water pollution mitigation.

Integrating nanotechnology with renewable energy and smart hybrid systems further enhances their sustainability potential.

Future research should prioritize the development of safe, recyclable, and economically viable nanomaterials to maximize effectiveness. Global initiatives should aim to harmonize standards, improve access, and support the responsible implementation of these technologies. Public education and awareness will be critical for achieving social acceptance and facilitating the broader adoption of nanotechnology in wastewater treatment.

## References


1. Abdel-Fatah MA. Nanofiltration systems and applications in wastewater treatment: Review article. Ain Shams Eng J. 2018;9(4):3077-3092. https://doi.org/10.1016/j.asej.2018.08.001
2. Adam AM, El-Magied MO, El-Aassy IE, et al. Pb(II), Cd(II) and Sn(II) Heavy Metals from Wastewater Using Novel Metal-Carbon-Based Composites. Crystals. 2021;11(8):882. https://doi.org/10.3390/cryst11080882
3. Adegoke KA, Adegoke RO, Adesina AO, et al. Bibliometric evaluation of nanoadsorbents for wastewater treatment and way forward in nanotechnology for clean water sustainability. Sci Afr. 2023;21:e01753. https://doi.org/10.1016/j.sciaf.2023.e01753
4. Agarwal A, Goyal A. Purification of Water Using Nanotechnology. J Mech Constr Eng. 2023;3(1):1-14. https://doi.org/10.54060/jmce.v3i1.27
5. Agboola O, Sadare OO, Muzenda E, et al. Theoretical performance of nanofiltration membranes for wastewater treatment. Environ Chem Lett. 2015;13(1):37-47. https://doi.org/10.1007/s10311-014-0486-y
6. Akbar A, Bhavani Lakshmi M, Ghosha M. Harnessing Spinel Ferrites: A Comprehensive Review of Their Role in Water Treatment. Environ Nanotechnol Monit Manag. 2024;22:101019.
7. Al-Mamun MR, Kader S, Islam MS, et al. Photocatalytic activity improvement and application of UV-TiO2 photocatalysis in textile wastewater treatment: A review. J Environ Chem Eng. 2019;7(5):103248. https://doi.org/10.1016/j.jece.2019.103248
8. Alomar M, Khalil AM, Al-Hazmi F, et al. Genipin Nanoparticles-Doped Reduced Graphene Oxide Membranes: A Promising Solution for Arsenic Ion Removal From Wastewater. Arab J Sci Eng. 2024;50(2):1123-1138. https://doi.org/10.1007/s13369-024-09634-x
9. Aly AA, Ibrahim MA, Salama AS, et al. Contaminants and salinity removal of olive mill wastewater using zeolite nanoparticles. Sep Sci Technol. 2018;53(11):1638-1653. https://doi.org/10.1080/01496395.2018.1425301
10. Amin MT, Alazba AA, Manzoor U. A review of removal of pollutants from water/wastewater using different types of nanomaterials. Adv Mater Sci Eng. 2014;2014:825910. https://doi.org/10.1155/2014/825910
11. Anwar Y, Asif M, Ali M, et al. Application of Nanostructured Materials for the Remediation of Microbes Contaminated Water and Sustainable Water Treatment. J Chem Environ. 2024;3(1):109-138. https://doi.org/10.56946/jce.v3i1.294
12. Ashraf S, Siddique M, Akhtar J, et al. Titanium-based nanocomposite materials for arsenic removal from water: A review. Heliyon. 2019;5(5):e01577. https://doi.org/10.1016/j.heliyon.2019.e01577
13. Babatunde DE, Bello SA, Adeyemi AO, et al. Environmental and Societal Impact of Nanotechnology. IEEE Access. 2020;8:4640-4667. https://doi.org/10.1109/ACCESS.2019.2961513
14. Baker C, Pradhan A, Pakstis L, et al. Synthesis and antibacterial properties of silver nanoparticles. J Nanosci Nanotechnol. 2005;5(2):244-249. https://doi.org/10.1166/jnn.2005.034
15. Bhat SA, Bashir O, Bandh SA, et al. Sustainable nanotechnology based wastewater treatment strategies: achievements, challenges and future perspectives. Chemosphere. 2022;288:132606. https://doi.org/10.1016/j.chemosphere.2021.132606
16. Bhat SA, Qadri H, Ahmad A, et al. Detection and treatment of emerging contaminants in wastewater. London: IWA Publishing; 2024. https://doi.org/10.2166/9781789063752
17. Brame J, Li Q, Alvarez PJJ. Nanotechnology-enabled water treatment and reuse: emerging opportunities and challenges for developing countries. Trends Food Sci Technol. 2011;22(11):618-624. https://doi.org/10.1016/j.tifs.2011.01.004
18. Bystrzejewska-Piotrowska G, Golimowski J, Urban PL. Nanoparticles: Their potential toxicity, waste and environmental management. Waste Manag. 2009;29(9):2587-2595. https://doi.org/10.1016/j.wasman.2009.04.001
19. Chae SR, Kim JH, Hwang YS, et al. Comparison of the photosensitivity and bacterial toxicity of spherical and tubular fullerenes of variable aggregate size. J Nanopart Res. 2011;13(10):5121-5127. https://doi.org/10.1007/s11051-011-0492-y
20. Chaturvedi S, Dave PN, Shah NK. Applications of nano-catalyst in new era. J Saudi Chem Soc. 2012;16(3):307-325. https://doi.org/10.1016/j.jscs.2011.01.015
21. Dabagh A, Boudaghi A, Khodadadi A, et al. Enhanced cationic/anionic dyes removal in wastewater by green nanocomposites synthesized from acid-modified biomass and CuFe2O4 nanoparticles: Mechanism, Taguchi optimization and toxicity evaluation. Environ Nanotechnol Monit Manag. 2024;22:101019. https://doi.org/10.1016/j.enmm.2024.101019
22. Danilczuk M, Lund A, Sadło J, et al. Conduction electron spin resonance of small silver particles. Spectrochim Acta A Mol Biomol Spectrosc. 2006;63(1):189-191. https://doi.org/10.1016/j.saa.2005.05.002
23. Dhermendra K, Tiwari A, Tiwari A, et al. Application of Nanoparticles in Waste Water Treatment. In: Proceedings of the International Conference on Nanotechnology. 2008:272-273.
24. Epelle EI, Obande MA, Adeleke AA, et al. Advances in the Applications of Nanomaterials for Wastewater Treatment. Environments. 2022;9(11):141. https://doi.org/10.3390/environments9110141
25. Essa WK, Yasin SA, Saeed A, et al. Taguchi L25 (54) Approach for Methylene Blue Removal by Polyethylene Terephthalate Nanofiber-Multi-Walled Carbon Nanotube Composite. Water.

2022;14(8):1242. https://doi.org/10.3390/w14081242
26. Falinski MM, Plata DL, Chopra SS, et al. Doing nano-enabled water treatment right: Sustainability considerations from design and research through development and implementation. Environ Sci Nano. 2020;7(11):3255-3278. https://doi.org/10.1039/D0EN00584C
27. Galdames A, Mendoza R, Oyarzún P, et al. Zero-valent iron nanoparticles for soil and groundwater remediation. Int J Environ Res Public Health. 2020;17(16):5817. https://doi.org/10.3390/ijerph17165817
28. Gao M, Zhang J, Wang Y, et al. Simple Aminated Modified Zeolite 4A Synthesized Using Fly Ash and Its Remediation of Mercury Contamination: Characteristics and Mechanism. Sustainability. 2022;14(23):15924. https://doi.org/10.3390/su142315924
29. Garcia-Segura S, Qu X, Alvarez PJJ, et al. Opportunities for nanotechnology to enhance electrochemical treatment of pollutants in potable water and industrial wastewater-a perspective. Environ Sci Nano. 2020;7(8):2178-2194. https://doi.org/10.1039/D0EN00194E
30. Gehrke I, Geiser A, Somborn-Schulz A. Innovations in nanotechnology for water treatment. Nanotechnol Sci Appl. 2015;8:1-17. https://doi.org/10.2147/NSA.S43773
31. Gupta P, Tamrakar G. An assessment of Application of Nanomaterials for Treating Emerging Contaminants in Water. Int J Tech Res Sci. 2020;Special(Issue3):36-41. https://doi.org/10.30780/specialissue-ICACCG2020/030
32. Gutierrez AM, Dziubla TD, Hilt JZ. Recent advances on iron oxide magnetic nanoparticles as sorbents of organic pollutants in water and wastewater treatment. Rev Environ Health. 2017;32(1-2):111-117. https://doi.org/10.1515/reveh-2016-0063
33. Gxaba SZ. Public Perceptions of Nanotechnology-enabled Water Treatment in a Mining Community in South Africa: A study of Bekkersdal. MSc Thesis. University of the Witwatersrand; 2019.
34. Hamdy A, Mostafa MK, Nasr M. Zero-valent iron nanoparticles for methylene blue removal from aqueous solutions and textile wastewater treatment, with cost estimation. Water Sci Technol. 2018;78(2):367-378. https://doi.org/10.2166/wst.2018.306
35. Hao L, Hu W, Zhang Y, et al. Recent advances in the application of iron-based adsorbents for wastewater treatment. RSC Adv. 2018;8(69):39545-39560. https://doi.org/10.1039/C8RA08512A
36. Horikoshi S, Serpone N. Can the photocatalyst TiO2 be incorporated into a wastewater treatment method? Background and prospects. Catal Today. 2020;340:334-346. https://doi.org/10.1016/j.cattod.2018.10.020
37. Hossain MDF, Akther N, Zhou Y. Recent advancements in graphene adsorbents for wastewater treatment: Current status and challenges. Chin Chem Lett. 2020;31(10):2525-2538. https://doi.org/10.1016/j.cclet.2020.05.011
38. Iravani S, Korbekandi H, Mirmohammadi SV, et al. Synthesis of silver nanoparticles: Chemical, physical and biological methods. Res Pharm Sci. 2014;9(6):385-406.
39. Theron J, Walker JA, Cloete TE. Nanotechnology and Water Treatment: Applications and Emerging Opportunities. Crit Rev Microbiol. 2008;34(1):43-69. https://doi.org/10.1080/10408410701710442
40. Jain K, Patel AS, Pardhi VP, et al. Nanotechnology in wastewater management: A new paradigm towards wastewater treatment. Molecules. 2021;26(6):1797. https://doi.org/10.3390/molecules26061797
41. Jain P, Pradeep T. Potential of silver nanoparticle-coated polyurethane foam as an antibacterial water filter. Biotechnol Bioeng. 2005;90(1):59-63. https://doi.org/10.1002/bit.20368
42. Jarosz R, Szerement J, Gondek K, et al. The use of zeolites as an addition to fertilisers - A review. CATENA. 2022;213:106125. https://doi.org/10.1016/j.catena.2022.106125
43. Jasaswini T, Satya Prasad SV, Srinivas V, et al. Recent advances in nanotechnology for wastewater treatment. Int J Res Publ Rev. 2024;5(2):372-373.
44. Jayakaran P, Nirmala GS, Govindarajan L. Qualitative and Quantitative Analysis of Graphene-Based Adsorbents in Wastewater Treatment. Int J Chem Eng. 2019;2019:9872502. https://doi.org/10.1155/2019/9872502
45. Jiang M, Li W, Zhang X, et al. The Role of Nanomaterials and Nanotechnologies in Wastewater Treatment: a Bibliometric Analysis. Nanoscale Res Lett. 2018;13:233. https://doi.org/10.1186/s11671-018-2649-4
46. Kamali M, Jahanbin M, Alavi-Borazjani SA, et al. Sustainability criteria for assessing nanotechnology applicability in industrial wastewater treatment: Current status and future outlook. Environ Int. 2019;125:261-276. https://doi.org/10.1016/j.envint.2019.01.055
47. Kanakaraju D, Glass BD, Oelgemöller M. Titanium dioxide photocatalysis for pharmaceutical wastewater treatment. Environ Chem Lett. 2014;12(1):27-47. https://doi.org/10.1007/s10311-013-0428-0
48. Kanchi S. Nanotechnology for Water Treatment. J Environ Anal Chem. 2014;1(2):1-2. https://doi.org/10.4172/2380-2391.1000e102
49. Khoshkerdar I, Esmaeili H. Adsorption of Cr(III) and Cd(II) ions using mesoporous cobalt-ferrite nanocomposite from synthetic wastewater. Acta Chim Slov. 2019;66(1):208-216. https://doi.org/10.17344/acsi.2018.4795
50. Kim JS, Kuk E, Yu KN, et al. Antimicrobial effects of silver nanoparticles. Nanomedicine. 2007;3(1):95-101. https://doi.org/10.1016/j.nano.2006.12.001
51. Kumari P, Alam M, Siddiqi WA. Usage of nanoparticles as adsorbents for waste water treatment: An emerging trend. Sustain Mater Technol. 2019;22:e00128. https://doi.org/10.1016/j.susmat.2019.e00128
52. Kurian M, Thankachan S. Structural diversity and applications of spinel ferrite core-shell nanostructures- A review. Open Ceram. 2021;8:100179. https://doi.org/10.1016/j.oceram.2021.100179
53. Lam WH, Tee LH, Ban ZH. A Facile and Rapid Immobilization Method of Titanium Dioxide-Alginate Composite for the Photocatalytic Removal of Reactive Black-5. Bull Chem React Eng Catal. 2024;19(2):230-241. https://doi.org/10.9767/bcrec.20133
54. Lead JR, Batley GE, Alvarez PJJ, et al. Nanomaterials in the environment: Behavior, fate, bioavailability, and effects-An updated review. Environ Toxicol Chem. 2018;37(8):2029-2063. https://doi.org/10.1002/etc.4147
55. Liang W, Wang M, Zhang X, et al. Application of zero-valent iron nanoparticles for the removal of aqueous zinc ions under various experimental conditions. PLoS ONE. 2014;9(1):e85686. https://doi.org/10.1371/journal.pone.0085686
56. Liau SY, Read DC, Pugh WJ, et al. Interaction of silver nitrate with readily identifiable groups: relationship to the antibacterial action of silver ions. Lett Appl Microbiol. 1997;25(4):279-283. https://doi.org/10.1046/j.1472-765X.1997.00219.x
57. Liu L, Chen X. Titanium Dioxide Nanomaterials: Self-Structural Modifications. Chem Rev. 2014;114(19):9890-9918. https://doi.org/10.1021/cr400624r
58. MacHado AB, Silva JF, Santos JC, et al. Applications of nanotechnology in water treatment. Rev Conhec Online. 2019;1:3-15. https://doi.org/10.25112/rco.v1i0.1706
59. Maharana KC, Acharya S. Nanotechnology in wastewater treatment: A comprehensive review. SSRN Electron J. 2024;5(2):372-373.
60. Mahmoodi NM, Saffar-Dastgerdi MH. Zeolite nanoparticle as a superior adsorbent with high capacity: Synthesis, surface modification and pollutant adsorption ability from wastewater. Microchem J. 2019;145:74-83. https://doi.org/10.1016/j.microc.2018.10.018
61. Mahmoud AS, Mostafa MK, Peters RW. A prototype of textile wastewater treatment using coagulation and adsorption

by Fe/Cu nanoparticles: Techno-economic and scaling-up studies. Nanomater Nanotechnol. 2021;11:1-21. https://doi.org/10.1177/18479804211041181
62. Mohadesi M, Shokri A. The application of modified nano-TiO2 photocatalyst for wastewater treatment: A review. Int J Environ Anal Chem. 2024;104(11):2571-2592. https://doi.org/10.1080/03067319.2022.2064751
63. Majid Z, AbdulRazak AA, Noori WAH. Modification of Zeolite by Magnetic Nanoparticles for Organic Dye Removal. Arab J Sci Eng. 2019;44(6):5457-5474. https://doi.org/10.1007/s13369-019-03788-9
64. Marzoq HAF, Al-Hasani AA, Al-Zubaidi AA, et al. Impact of Photo-remediation on Anthracene PAHs in treated wastewater using ZnO/TiO2/H2O2 Catalysis. Open Access Res J Sci Technol. 2024;11(1):59-70. https://doi.org/10.53022/oarjst.2024.11.1.0068
65. Mohamed Noor MH, Ngadi N, Abdul Rani NA, et al. Assessing the effectiveness of magnetic nanoparticles coagulation/flocculation in water treatment: a systematic literature review. Int J Environ Sci Technol. 2022;19(7):6935-6956. https://doi.org/10.1007/s13762-021-03369-0
66. Mohammad AW, Teow YH, Ang WL, et al. Nanofiltration membranes review: Recent advances and future prospects. Desalination. 2015;356:226-254. https://doi.org/10.1016/j.desal.2014.10.043
67. Mohammed L, Gomaa HG, Ragab D, et al. Magnetic nanoparticles for environmental and biomedical applications: A review. Particuology. 2017;30:1-14. https://doi.org/10.1016/j.partic.2016.06.001
68. Moussa F, Trinh TM, Moussa A, et al. Early effects of C60 administration in Swiss mice: A preliminary account for in vivo C60 toxicity. Fullerene Sci Technol. 1996;4(1):21-29. https://doi.org/10.1080/10641229608001534
69. Mpongwana N, Rathilal S. A Review of the Techno-Economic Feasibility of Nanoparticle Application for Wastewater Treatment. Water. 2022;14(10):1550. https://doi.org/10.3390/w14101550
70. Mulyanti R, Susanto H. Wastewater treatment by nanofiltration membranes. IOP Conf Ser Earth Environ Sci. 2018;142:012017. https://doi.org/10.1088/1755-1315/142/1/012017
71. Nasir AM, Wahab RA, Karim ZA, et al. Recent progress on fabrication and application of electrospun nanofibrous photocatalytic membranes for wastewater treatment: A review. J Water Process Eng. 2021;40:101878. https://doi.org/10.1016/j.jwpe.2020.101878
72. Nasr M, Balme S, Eid C, et al. Recent Progress on Titanium Dioxide Nanomaterials for Photocatalytic Applications. J Nanomater. 2021;11(8):3023-3047. https://doi.org/10.1002/cssc.201800874
73. Oatley-Radcliffe DL, Walters M, Ainscough TJ, et al. Nanofiltration membranes and processes: A review of research trends over the past decade. J Water Process Eng. 2017;19:164-171. https://doi.org/10.1016/j.jwpe.2017.07.026
74. Olvera RC, Barrera A, Ruíz M, et al. Review of nanotechnology value chain for water treatment applications in Mexico. Resour Effic Technol. 2017;3(1):1-11. https://doi.org/10.1016/j.reffit.2017.01.008
75. Palani G, Ponnusamy S, Sivasubramanian S, et al. Silver Nanoparticles for Waste Water Management. Molecules. 2023;28(8):3520. https://doi.org/10.3390/molecules28083520
76. Pandey K, Sharma S, Saha S. Advances in design and synthesis of stabilized zero-valent iron nanoparticles for groundwater remediation. J Environ Chem Eng. 2022;10(3):107993. https://doi.org/10.1016/j.jece.2022.107993
77. Pasinszki T, Krebsz M. Synthesis and application of zero-valent iron nanoparticles in water treatment, environmental remediation, catalysis, and their biological effects. Nanomaterials. 2020;10(5):917. https://doi.org/10.3390/nano10050917
78. Patel AK, Pinos-Vélez VP, Cipriani-Avila I. Editorial: Developments in managing emerging pollutants in natural waters: a focus on low- and middle-income regions. Front Environ Sci. 2024;12:1420243. https://doi.org/10.3389/fenvs.2024.1420243
79. Peng W, Li H, Liu Y, et al. A review on heavy metal ions adsorption from water by graphene oxide and its composites. J Mol Liq. 2017;230:496-504. https://doi.org/10.1016/j.molliq.2017.01.064
80. Petrik L, Hlabangana N, Nkwonta O, et al. Silver/Zeolite Nano Composite-Based Clay Filters. Water Research Commission (WRC); 2012.
81. Pirbavepour M, Mostafa MK, Nasr M, et al. Removal of Humic Substances from Aqueous Solutions Using Carbon Quantum Dots and Activated Carbon Derived by Watermelon Rind. J Water Environ Nanotechnol. 2024;9(4):367-384.
82. Qasim M, Aslam M, Raza A, et al. Biogenic Nanoparticles at the Forefront: Transforming Industrial Wastewater Treatment with TiO2 and Graphene. Sch J Agric Vet Sci. 2024;11(5):56-76. https://doi.org/10.36347/sjavs.2024.v11i05.002
83. Rafieenia R, Chen J, Zhang Y, et al. Editorial: Microbial communities for bioenergy recovery from wastes and waste streams. Front Energy Res. 2024;12:1383513. https://doi.org/10.3389/fenrg.2024.1383513
84. Romero-Franco M, Godwin HA, Bilal M, et al. Needs and challenges for assessing the environmental impacts of engineered nanomaterials (ENMs). Beilstein J Nanotechnol. 2017;8(1):989-1014. https://doi.org/10.3762/bjnano.8.101
85. Sadeghi-Kiakhani M, Arami M, Gharanjig K. Dye removal from colored-textile wastewater using chitosan-PPI dendrimer hybrid as a biopolymer: Optimization, kinetic, and isotherm studies. J Appl Polym Sci. 2013;127(4):2607-2619. https://doi.org/10.1002/app.37615
86. Sahu J, Mohanta YK, Panda SK, et al. Current Perspectives and Future Prospects of Nano-Biotechnology in Wastewater Treatment. Sep Purif Rev. 2021;50(2):139-158. https://doi.org/10.1080/15422119.2019.1630430
87. Saini AS, Bhatia PG. Applications of Magnetic Nanoparticles for Heavy Metal Ion Removal from Wastewater: A Review. Carbon Sci Technol. 2024;4(3):196-208. https://doi.org/10.69626/csa.2024.0196
88. Saleem H, Zaidi SJ. Developments in the application of nanomaterials for water treatment and their impact on the environment. Nanomaterials. 2020;10(9):1764. https://doi.org/10.3390/nano10091764
89. Saliby IJ El, Okour Y, Shon HK, et al. Nanotechnology in wastewater treatment: A review. Desalination Water Treat. 1999;15(1-3):1-10.
90. Salim N, Badri K, Ariffin H, et al. PVDF based Nanocomposite Membranes: Application towards Wastewater treatment. Madridge J Nanotechnol Nanosci. 2019;4(1):139-147. https://doi.org/10.18689/mjnn-1000128
91. Sangalang RH. Nanotechnology for Clean and Safe Water: (A Review). Orient J Chem. 2022;38(2):227-237. https://doi.org/10.13005/ojc/380202
92. Sayes CM, Fortner JD, Guo W, et al. The differential cytotoxicity of water-soluble fullerenes. Nano Lett. 2004;4(10):1881-1887. https://doi.org/10.1021/nl0489586
93. Shi J, Yang Z, Dai H, et al. Preparation and application of modified zeolites as adsorbents in wastewater treatment. Water Sci Technol. 2017;2017(3):621-635. https://doi.org/10.2166/wst.2018.249
94. Shukla S, Khan R, Daverey A. Synthesis and characterization of magnetic nanoparticles, and their applications in wastewater treatment: A review. Environ Technol Innov. 2021;24:101924. https://doi.org/10.1016/j.eti.2021.101924
95. Sikiru S, Oladokun SO, Suleiman MA, et al. A comprehensive review on nanotechnology application in wastewater treatment a case study of metal-based using green synthesis. J Environ

Chem Eng. 2022;10(4):108065. https://doi.org/10.1016/j.jece.2022.108065

96. Singh A, Kosalge SS, Bhatia PG. Applications of Magnetic Nanoparticles for Heavy Metal Ion Removal from Wastewater: A Review. Carbon Sci Technol. 2024;4(3):196-208. https://doi.org/10.69626/csa.2024.0196
97. Singh P, Kumar R, Sharma A, et al. Nanotechnology: Social Acceptance, Cultural Impact and Privacy. In: Singh P, editor. Nanotechnology in Modern Society. Springer; 2024. https://doi.org/10.1007/978-981-97-6184-5_2
98. Tahoon MA, El-Sayed A, Al-Ghamdi AA, et al. Effective heavy metals removal from water using nanomaterials: A review. Processes. 2020;8(6):645. https://doi.org/10.3390/pr8060645
99. Tijani JO, Olugbenga AG, Mustapha S, et al. Adsorptive and photocatalytic properties of green synthesized ZnO and ZnO/NiFe2O4 nanocomposites for tannery wastewater treatment. Niger J Technol Dev. 2020;17(4):312-322. https://doi.org/10.4314/njtd.v17i4.10
100. Tripathy J, Mishra A, Panda SK, et al. Advances in Nanoparticles and Nanocomposites for Water and Wastewater Treatment: A Review. Water. 2024;16(11):1481. https://doi.org/10.3390/w16111481
101. Umejuru EC, Makhado E, Tichapondwa SM, et al. Application of zeolite based nanocomposites for wastewater remediation: Evaluating newer and environmentally benign approaches. Environ Res. 2023;231(P1):116073. https://doi.org/10.1016/j.envres.2023.116073
102. Ursino C, Castro-Muñoz R, Drioli E, et al. Progress of nanocomposite membranes for water treatment. Membranes. 2018;8(2):18. https://doi.org/10.3390/membranes8020018
103. Vanlalveni C, Lallianrawna S, Biswas A, et al. Green synthesis of silver nanoparticles using plant extracts and their antimicrobial activities: a review of recent literature. RSC Adv. 2021;11(5):2804-2837. https://doi.org/10.1039/D0RA09941D
104. Vishnu D, Karthikeyan R, Sivakumar P, et al. Comparison of surface-engineered superparamagnetic nanosorbents with low-cost adsorbents of cellulose, zeolites and biochar for the removal of organic and inorganic pollutants: a review. Environ Chem Lett. 2021;19:3181-3208. https://doi.org/10.1007/s10311-021-01201-2
105. Xiong LB, Li JL, Yang B, et al. Ti3+ in the surface of titanium dioxide: Generation, properties and photocatalytic application. J Nanomater. 2012;2012:831524. https://doi.org/10.1155/2012/831524
106. Yang K, Chen B, Zhu L, et al. Application of graphene-based materials in water purification: from the nanoscale to specific devices. Environ Sci Nano. 2018;5(6):1264-1297. https://doi.org/10.1039/C8EN00194D
107. Yurekli Y. Removal of heavy metals in wastewater by using zeolite nano-particles impregnated polysulfone membranes. J Hazard Mater. 2016;309:53-64. https://doi.org/10.1016/j.jhazmat.2016.01.064
108. Zafar AM, Ali A, Ahmad W, et al. Groundwater remediation using zero-valent iron nanoparticles (nZVI). Groundw Sustain Dev. 2021;15:100694. https://doi.org/10.1016/j.gsd.2021.100694
109. Zahid M, Rashid A, Akram S, et al. A Comprehensive Review on Polymeric Nano-Composite Membranes for Water Treatment. J Membr Sci Technol. 2018;8(1):1000179. https://doi.org/10.4172/2155-9589.1000179
110. Zamel D, Khan AU, Hassan AU, et al. Nanoparticles, Nanofibers and Metal-Organic Frameworks (MOFs) as Contaminants Removal in Wastewater Treatment. SSRN Electron J. 2022:1-12. https://doi.org/10.2139/ssrn.4180100
111. Zhang H, Wang J, Chen Y, et al. Drawing on Membrane Photocatalysis for Fouling Mitigation. ACS Appl Mater Interfaces. 2021;13(13):14844-14865. https://doi.org/10.1021/acsami.1c01131
112. Zhang T, Wang X, Zhang X. Recent progress in TiO2-mediated solar photocatalysis for industrial wastewater treatment. Int J Photoenergy. 2014;2014:607954. https://doi.org/10.1155/2014/607954
113. Zhao X, Liu W, Cai Z, et al. An overview of preparation and applications of stabilized zero-valent iron nanoparticles for soil and groundwater remediation. Water Res. 2016;100:245-266. https://doi.org/10.1016/j.watres.2016.05.019