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Enhanced wastewater treatment using metal-based on nanoparticles: a comprehensive study

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ABSTRACT

The escalating contamination of global water resources from industrial, agricultural, and domestic effluents underscores the urgent need for innovative wastewater treatment strategies. Metal-based nanoparticles (NPs) have revolutionized water purification because of their large surface area, strong reactivity, and adjustable physicochemical properties. This review explores the applications of NPs, such as zinc, iron, silver, titanium dioxide, cerium oxide, manganese oxide, and magnesium oxide in removing heavy metals, dyes, organic pollutants, and microbial pathogens from wastewater. The key mechanisms, including adsorption, filtration, photocatalysis, and redox reactions were critically analyzed, highlighting their superior efficiency in pollutant removal and water purification. The review also emphasized recent advancements in hybrid nanocomposites and functionalized NPs, which enhance selectivity and removal performance. Factors, such as nanoparticle size, surface charge, pH, and contact time influencing pollutant removal efficiency. Photocatalysis and redox mechanisms stand out for their eliminating complex pollutants into non-toxic byproducts, making them invaluable in addressing bioaccumulation and environmental risks. Despite these promising advancements, challenges persist, including potential nanoparticle toxicity, environmental persistence, and the scalability of these technologies. Future research should prioritize green synthesis methods, cost-effective production, and long-term environmental impact assessments. Integrating NPs with advanced treatment technologies, such as membrane filtration and oxidation processes, could offer a sustainable and scalable solution to global water scarcity and pollution. This review underscores the critical role of nanotechnology in developing efficient, eco-friendly wastewater treatment systems to ensure water security and environmental sustainability.

Keywords: *Nanoparticles, Wastewater treatment, Pollutant removal, Photocatalysis, Water purification.*

1. Introduction

Water is indispensable for life on Earth, and access to sanitary water is critical for public health [1]. While modern advancements have significantly enhanced our quality of life, they have also contributed to the proliferation of harmful substances and contaminants, posing serious risks to living organisms [2, 3]. In countries, namely India, over 80% of infections are waterborne, primarily attributed to microbial contamination in drinking water [4, 5]. According to the World Health Organization, drinking water must have zero total and fecal coliform counts per 100 mL sample, warranting immediate intervention if any pathogens are detected [6,7]. In addition to microbial contamination, the presence of toxic metal ions, such as Hg^{2+}, Pb^{2+}, Cr^{3+}, Cr^{6+}, Ni^{2+}, Co^{2+}, Cu^{2+}, Cd^{2+}, Ag^{+}, As^{5+}, and As^{3+} in wastewater highlights the urgent need for comprehensive treatment strategies [3, 8, 9]. Traditional wastewater treatment methods include adsorption [10, 11], precipitation [12, 13], ion exchange [14, 15], reverse osmosis [16, 17], electrochemical treatments [18, 19], membrane filtration [20, 21], evaporation [22, 23], flotation [24, 25], oxidation [19, 26], and biosorption [27, 28]. However, advanced techniques, such as membrane filtration and reverse osmosis often involve high costs, making them less accessible for widespread application. Given the escalating pollution levels from household and industrial sources, there is an urgent demand for innovative treatment approaches that are not only efficient and effective but also economically viable [8].

Recent research has increasingly focused on developing nanoparticle (NP)-based adsorbents for efficient pollutant removal [29,30]. Emerging advancements highlight the potential of nanoparticles (NPs) [31], Nano-sorbents [32,33], and nano-filtration [34,35] to significantly improve water quality. Among these, magnetite NPs have demonstrated exceptional promise in wastewater treatment, complementing their established applications in magnetic recording, MRI, and targeted drug delivery [33]. The toxicity of various metals presents significant challenges, with arsenic contamination in drinking water being particularly concerning due to its severe health impacts, including cancer and neurological disorders. Conventional adsorption techniques often fail to reduce arsenic levels below the World Health Organization's safety threshold of 10 $\mu g/L$ [36]. However, sorption methods employing novel sorbents are gaining traction due to their high efficiency and cost-effectiveness. In particular, magnetic iron oxide-based materials have emerged as effective alternatives for arsenic remediation, with NPs demonstrating remarkable efficacy [2, 33]. Industrial effluents pose additional hazards, containing substances, such as azo dyes, including organic compounds with the functional group

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R–N=N–R′, where R and R′ are typically aryl or substituted aryl groups [37, 38] and chromium ions. These pollutants necessitate the development of advanced adsorbents capable of targeting specific contaminants, namely phosphate ions to prevent eutrophication. Adsorption is crucial in mitigating phosphate pollution, reinforcing its importance in water treatment strategies [39].

NPs, such as zinc oxide and silver oxide are extensively utilized across various industries, including textiles [40], pharmaceuticals [41, 42], and wastewater treatment [43]. Advances in nanotechnology have enabled the synthesis and characterization of non-toxic NPs smaller than 10 nm. These nanoscale materials are particularly suited for the removal of organic [44, 45], inorganic [46, 47], and metal [48, 49] contaminants from water, owing to their small size, exceptional adsorption capacity, enhanced chemical reactivity, and high surface area-to-volume ratio [50]. Copper oxide (Cu_2O) and its nanowires are emerging as promising candidates for wastewater treatment, thanks to their availability, scalability, and non-toxic nature [51, 52]. Similarly, cupric oxide (CuO) NPs have demonstrated significant potential for arsenic removal [53]. Zinc oxide (ZnO) NPs have gained considerable attention for their potent antimicrobial properties, making them valuable in water purification applications [54, 55]. Silicon (Si) NPs offer a robust, resilient, and biologically inert system for the photocatalytic oxidation of pollutants, further expanding the versatility of nanotechnology in wastewater treatment [54, 56]. Additionally, applying silver [57] and gold NPs [58] has shown remarkable effectiveness in addressing critical contaminants, such as pesticides, heavy metals, and microbes. Among these, silver NPs stand out for their strong antibacterial properties, which remain effective even at low concentrations [39, 50].

Membrane-based purification techniques have emerged as alternatives to traditional methods, such as chemical precipitation and granular media filtration. The advancement of membrane-based technology hinges on the development of innovative membrane materials. Nanotechnology has facilitated the creation of membranes with enhanced permeability, selectivity, and resistance to fouling, primarily through the incorporation of functionalized NPs [59, 60]. NPs play a pivotal role in removing a wide range of contaminants, including metals, nutrients, cyanides, organic compounds, algal toxins, viruses, bacteria, parasites, and antibiotics. Four major categories of nanomaterials frequently utilized in wastewater treatment include zeolites [61, 62], dendrimers [63, 64], carbonaceous nanomaterials [65, 66], and metal-containing NPs [67, 68]. Among these, carbon nanotubes and nanofibers have demonstrated exceptional efficiency in water purification applications [60].

Building on this premise, the present study aims to provide a comprehensive overview of the application of NPs in wastewater remediation and treatment, focusing on key factors influencing their performance. This study specifically examines the role of NPs in removing mineral pollutants from wastewater, synthesizing findings from research conducted since 2020. A series of tables consolidate these investigations for clarity and comparison. The data reveal that most research has been conducted on synthetic wastewater solutions using batch-scale experiments. Notably, the application of NPs significantly enhances removal efficiency and enables the simultaneous targeting of multiple contaminants. The findings suggest that adsorption, combined with redox processes, remains the predominant mechanism for removing inorganic pollutants. NPs have demonstrated remarkable success in wastewater treatment due to their high removal efficiency, extensive surface area, ease of separation, and cost-effectiveness. These attributes underscore the potential of NPs as a powerful tool for addressing complex wastewater challenges.

2. Application of nanoparticles in wastewater treatment

Nanotechnology plays a pivotal role in addressing global challenges related to energy, water, and health. Its application in environmental cleanup offers numerous advantages, including early intervention in pollution treatment, highly efficient nanomaterials, enhanced sensing accuracy due to their nanoscale size, and cost-effectiveness through in situ applications with low energy requirements. Nanotechnology also simplifies treatment processes and reduces spatial demands [59]. In the context of wastewater treatment, nanotechnology employs the following innovative approaches [69]:

- NPs as Nano-adsorbents: Sequestering and adsorbing contaminants, particularly heavy metals.
- NPs as Nano-catalysts: Oxidizing and decomposing pollutants.
- Nanoparticle-Enhanced Membrane Filtration: Integrating NPs with membrane filtration methods to improve performance.

NPs as Nano-sensors: Enabling rapid and accurate detection of viruses and diseases.

These methods highlight the transformative potential of nanotechnology in achieving efficient and sustainable wastewater treatment solutions. As illustrated in Fig. 1, NPs, with their small size and high surface area, offer numerous active sites for interactions with various chemical species, making them highly effective adsorbents for wastewater pollutants. Their nanoscale dimensions accelerate adsorption rates and improve efficiency through enhanced surface accessibility and dispersion [69,70].

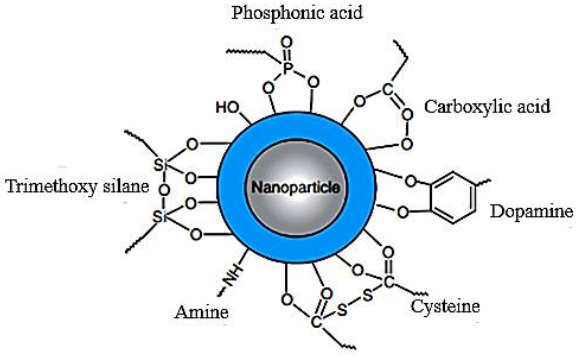

Fig. 1. Multifunctionality of metal oxide nanoparticle surfaces, highlighting their ability to act as efficient adsorbents due to their high surface area, tunable surface charge, and active sites that enable interactions with a variety of chemical species. These properties facilitate the adsorption and removal of diverse pollutants in wastewater treatment [69].

The solution's pH plays a critical role in modulating the surface functionality of metal and metal oxide NPs, thereby influencing their adsorption capacity. For example, at higher pH levels, negatively charged Fe_3O_4 nano-adsorbents exhibit improved adsorptive removal of heavy metals, whereas a positive surface charge at lower pH inhibits adsorption [71, 72]. Electrostatic interactions between the nano-adsorbent surfaces and ions are fundamental to the adsorption of metal ions or functionalized pollutants. Variations in pH not only affect the surface charge of Nano-adsorbents but also influence their ability to adsorb organic molecules. Surface-modified Nano-adsorbents, enhanced with surfactants, such as cetyltrimethylammonium bromide, demonstrate superior removal efficiency for complex substances, namely As^{3+}. Furthermore, adjusting the solution's pH facilitates both the recovery of adsorbate and the regeneration of Nano-adsorbents, extending their usability. Various metals, including bimetallic systems, metal oxides, and mixed metal oxides, have proven effective in removing a broad spectrum of pollutants from wastewater [73,74].

Iron-based NPs are extensively utilized in environmental cleanup due to their availability, magnetic properties, and multifunctional surfaces. These NPs exhibit superior adsorption affinity, capacity, and faster reaction rates than many conventional adsorbents. Among iron oxides, oxyhydroxides, and hydroxides, maghemite (γ-Fe_2O_3) and magnetite ($FeO.Fe_2O_3$), stand out for their efficiency and practicality. Their magnetic properties enable easy post-use collection using a magnet, making them particularly appealing for wastewater treatment applications. However, one significant challenge is NP aggregation, which can compromise their effectiveness and reduce their feasibility in

large-scale applications. Strategies to address this issue include on-site preparation, the use of supports, such as clay, or the addition of capping agents, namely surfactants. Clay-supported NPs, in particular, enhance dispersion, improve storage stability, and facilitate pelletization for practical handling and application [60, 71, 74].

3. Type of NPs in wastewater treatment

NPs are not only effective in removing organic pollutants but also play a crucial role in the removal of toxic heavy metals, such as copper (Cu), mercury (Hg), chromium (Cr), and other metals commonly found as inorganic pollutants in wastewater. Additionally, NPs are increasingly utilized for the removal and recovery of nutrients from wastewater. Recently, several types of NPs have been incorporated into the development of colorimetric sensors, providing a simple, cost-effective means to detect and eliminate heavy metals [59]. This study reviews the effects of NPs on removing mineral pollutants from wastewater, incorporating data from research conducted since 2020.

A series of tables consolidate these findings for comparison. The data reveals that most research has been conducted on synthetic wastewater solutions using batch-scale experiments. However, it is important to emphasize that the use of NPs significantly enhances removal efficiency and enables the targeting of a wide range of contaminants. These results suggest that the primary mechanism for eliminating inorganic pollutants continues to be adsorption, often combined with redox processes. Due to their high removal efficiency, larger surface area, ease of separation, and cost-effectiveness, NPs have proven highly successful in wastewater cleanup (Fig. 2).

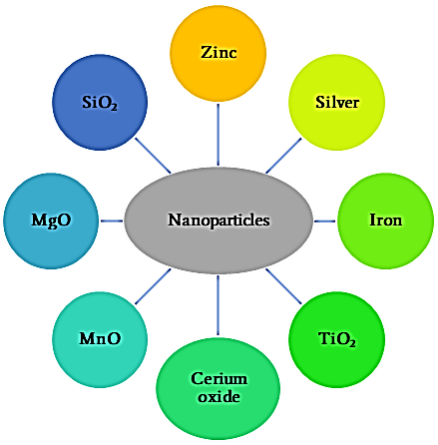

Fig. 2. Various types of NPs were employed in wastewater treatment, illustrating their diverse applications in removing organic and inorganic pollutants, enhancing adsorption capacity, and facilitating contaminant recovery and detection.

3.1. Zinc NPs

Zinc NPs (Zn NPs) are increasingly used in various products, such as sunscreen, packaging, paints, plastics, food supplements, and cosmetics, leading to their indirect introduction into ecosystems. Due to their stronger reduction potential than iron (Fe), zinc NPs are considered an effective alternative to iron-based NPs in wastewater treatment. Negative reduction potential and higher reactivity make zinc a more potent reductant than iron. In wastewater treatment, the rate of pollutant degradation using Zn NPs is significantly higher than that observed with zerovalent iron (ZVI) NPs. Most research on using Zn NPs in wastewater treatment has focused on dehalogenation processes. Several studies have demonstrated that Zn NPs can effectively reduce pollutants, particularly in the breakdown of halogenated and chlorinated organic compounds [75–77].

The photocatalytic degradation of organic pollutants using ZnO/MCM-41 involves several critical steps. Upon exposure to light, zinc oxide NPs absorb photons, which excites electrons from the valence band to the conduction band, leaving behind positively charged holes. These excited electrons and holes then generate reactive oxygen species (ROS), such as hydroxyl radicals (OH^*) and superoxide ions (O_2^-). The high surface area and mesoporous structure of MCM-41 further enhance the dispersion of ZnO NPs, promoting greater light absorption and improving interactions with pollutants. Organic contaminants adsorbed onto the surface of ZnO/MCM-41 undergo oxidation reactions, primarily driven by ROS, and are ultimately degraded into harmless byproducts, namely CO_2 and H_2O. This combined photocatalytic system not only boosts efficiency but also enhances the stability of the degradation process, making it highly effective in breaking down recalcitrant organic pollutants in wastewater (Fig. 3).

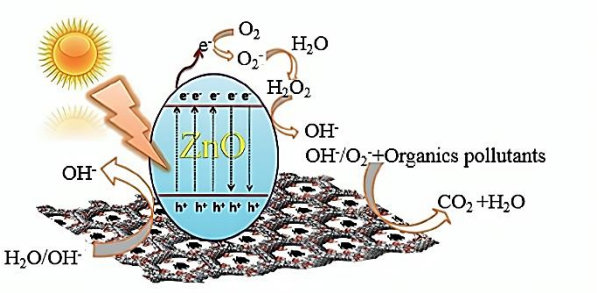

Fig. 3. The mechanism of photocatalytic degradation of organic pollutants using ZnO/MCM-41 illustrating the excitation of electrons and the generation of reactive oxygen species (ROS) that drive the oxidation of organic contaminants, resulting in the formation of harmless byproducts, such as CO_2 and H_2O [78].

Based on the data presented in Table 1, zinc oxide nanoparticles (ZnO NPs) exhibit significant potential for purifying mineral pollutants.

Notable findings include the high efficacy of ZnO particles with a size below 100 *nm* and a solution pH of approximately 4.8 in removing copper (Cu (II)) and arsenic (III) ions from aqueous solutions (Fig. 4). Additionally, the IL/ZnO composite has proven effective in removing nickel, achieving a removal rate of approximately 92.5% within 90 minutes at a pH of 6. Furthermore, ZnO NPs with an average size of 62.03 *nm* have demonstrated successful removal of both arsenic (III) and arsenic (V) from water. However, to remove mercury (a highly toxic pollutant), a shorter contact time and an increased quantity of ZnO particles may be required to optimize the process and enhance removal efficiency [75–77].

ZnO NPs have demonstrated remarkable success in eliminating a wide range of pollutants, including copper (Cu (II)) [75, 82], arsenic (III) ions [77, 79, 80], nickel [76], and mercury [81, 83]. Notably, in certain applications, such as the rapid removal of copper ions (Cu (II)), ZnO achieved an impressive removal rate of approximately 98.4% within just 5 minutes, highlighting its fast and efficient pollutant removal capabilities. The particle size of ZnO plays a crucial role in its efficiency, with smaller particles generally exhibiting superior removal performance [75]. Additionally, the pH of the solution significantly influences the pollutant removal efficiency of ZnO, particularly in the cases of arsenic and mercury. Furthermore, the pH of the environment significantly impacts ZnO's pollutant removal efficiency, particularly in cases involving arsenic and mercury. In conclusion, these findings emphasize the substantial potential of ZnO NPs in purifying contaminated water, offering an effective solution for water treatment systems. Based on the data, it was observed that a shorter reaction time, coupled with using an ionic solution, enhances the efficiency of nickel ion removal from wastewater [75–77, 79–82].

In studies focused on arsenic ion removal, several factors, such as pH, reaction time, and nanoparticle size to affect removal efficiency significantly. For example, under conditions of pH 7, a 60-minute reaction time, and NPs sized between 25-30 nm, the removal efficiency reached an impressive 99.90%. In contrast, a similar study with a shorter reaction time showed a reduced efficiency of 90.3%.

Table 1. The purification of heavy metals in the ions form and mineral pollutants by Zn NPs.

Type of NPs	Contaminant removed	Contact time (min)	Removal efficiency (%)	Size particle (nm)	pH	Ref.
ZnO	Cu (II)	5	98.4	<100	4.8	[75]
IL/ZnO	nickel	90	92.5	-	6	[76]
ZnO	nickel	120	81	-	6	[76]
ZnO	Arsenic (III)	60	99.90	25-30	7	[77]
ZnO	Arsenic (III)	40	90.3	25-30	7	[79]
ZnO	As (III)	40	93	62.03 ±4.06	4	[80]
ZnO	As (V)	40	95	62.03 ± 4.06	4	[80]
ZnO	Mercury (II)	15	-	87.2	-	[81]
ZnO/CdS	Mercury (II)	15	-	87.2	-	[81]
ZnO	Copper	15	>95	43.3	4	[82]

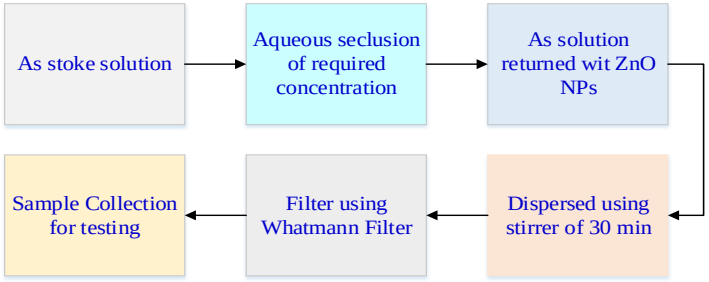

Fig. 4. The graphical representation of arsenic adsorption from wastewater using ZnO NPs, illustrating the removal efficiency of ZnO at varying conditions and showcasing its effectiveness in purifying arsenic-contaminated water [79].

In studies focused on arsenic ion removal, several factors, such as pH, reaction time, and nanoparticle size to affect removal efficiency significantly. For example, under conditions of pH 7, a 60-minute reaction time, and NPs sized between 25-30 nm, the removal efficiency reached an impressive 99.90%. In contrast, a similar study with a shorter reaction time showed a reduced efficiency of 90.3%.

Additionally, under more acidic conditions (pH 4), with larger NPs and a shorter reaction time, the removal efficiency was 93%. A comparison of these studies indicates that smaller nanoparticle sizes, longer reaction times, and neutral pH conditions tend to lead to higher removal efficiency for arsenic ions. On the other hand, in a separate study at pH 7, with a 40-minute reaction time and nanoparticles sized between 25-30 nm, the removal efficiency was 90.3%. However, at pH 4, with NPs sized 62.03 nm and the same reaction time, the removal efficiency increased to 93%. These findings suggest that lower pH and larger nanoparticle sizes contribute to higher arsenic ion removal efficiency [77, 79, 80].

3.2. Iron NPs

Zero-valent iron (ZVI) NPs have demonstrated significant potential in developing remediation systems for on-site wastewater treatment. These NPs have been shown to effectively detoxify various substances, including vinyl chloride, carbon tetrachloride, hexachlorocyclohexane (lindane), chlorinated organic compounds (COCs), and trichloroethane. Most of the research on ZVI NPs focuses on their application in reductive dehalogenation processes in wastewater, owing to their strong and cost-effective electron-donating properties. In anaerobic environments, ZVI NPs are oxidized by water or protons, producing Fe (II) and hydrogen gas (H_2), which act as powerful reducing agents to degrade pollutants.

The Fe (II) produced is then oxidized to Fe (III), forming $Fe(OH)_3$, an efficient flocculant that aids in removing both organic and inorganic pollutants from ecosystems. Additionally, ZVI NPs generate reactive oxygen species, such as hydroxyl radicals and hydrogen peroxide, when they oxidize and break down various organic pollutants. Despite these advantages, ZVI NPs have some limitations, including oxidation within the pollutant degradation system, aggregation, and challenges in separation. To enhance the reactivity, dispersibility, and stability of ZVI nanoparticles in these systems, several strategies are being explored, such as surface coating, emulsification, doping with essential metal ions, and conjugation with supports [84–86].

Due to its large surface area and high reactivity, nano-zero-valent iron (n ZVI) effectively interacts with cadmium ions in water, converting them into less toxic or immobilized forms. This process occurs through adsorption and redox reactions, where nZVI functions as both an adsorbent and a reductant. Once cadmium is removed, it can either be recovered or transformed into cadmium-based compounds suitable for energy applications, such as photo-electrochemical cells. These recovered cadmium compounds are integrated into the semiconductor layers of solar cells, enhancing their photo-electrochemical performance by improving electron mobility and light absorption. This process exploits the unique properties of cadmium to optimize energy conversion (Fig. 5).

Table 2 highlights the effectiveness of various types of iron NPs, such as Fe_3O_4 @Ag@MESNa, Fe_3O_4 @EPS, JC- Fe_3O_4 , $Fe_3O_4@SiO_2$@GLYMO(S)-en, in removing a wide range of pollutants, including Hg^{2+}, PO_4^{3-}, Co^{2+}, Cu^{2+}, Pb^{2+}, Cd^{2+}, and Cr (VI) each demonstrating varying degrees of efficiency and contact times. Additionally, NPs, namely Fe NPs, n ZVI-NPs, and Fe/Cu NPs show strong performance in removing pollutants, such as Pb (II), Cr (VI), arsenic, and Cu, achieving different removal percentages. Key factors influencing removal efficiency, include particle size, pH, dosage, contact time, and the type of pollutant. For instance, Fe_3O_4@MgO exhibits remarkable efficiency in removing As (V) at pH levels ranging from 2 to 11. The size of the NPs, typically between 10 and 100 nm, is crucial in determining pollutant removal efficiency in certain cases.

The results indicate that the removal efficiency of Hg (II) ions by composite Fe_3O_4 NPs improves, with no significant difference observed between single and composite Fe_3O_4NPs. According to the data in Table 2, the elimination of Pb(II) using various types of iron NPs (magnetic, composite, etc.)—with nanoparticle sizes ranging from 25 to 100 nm, reaction durations between 30 and 80 minutes, and pH levels from 2 to 7—achieves the highest Pb (II) removal efficiency. Moreover, there is no notable variation in Pb (II) removal efficiency across different forms of NPs.

Table 2. The purification of Heavy metals in the ions form and mineral pollutants by ZVI NPs.

Type of NP	Contaminant removed	Contact time (s)	Removal efficiency	Size particle (nm)	pH	Ref.
Fe_3O_4@Ag@MESNa	Hg ++	30	100%	-	6.2	[85]
Fe_3O_4@EPS	PO_4^{2-}	46800	91%	10-20	7	[84]
JC- Fe_3O_4 and CT- Fe_3O_4 NPs	Co^{2+} & Cu^{2+}	7200	513.7 mg/g for Co^{2+} and 463.23 mg/g for Cu^{2+}	20-42	7	[86]
Superparamagnetic Fe_3O_4@SiO_2@GLYMO(S)-en	Pb^{2+}	3300	93.5 mg/g	-	-	[88]
Superparamagnetic Fe_3O_4@SiO_2@GLYMO(S)-en	Cd^{2+}	3300	80.64 mg/g	-	-	[88]
DES/GO-Fe_3O_4 nanohybrid	Pb^{2+}	1200	80%	-	-	[89]
core-shell $MnFe_2O_4$@TiO_2	Cu^{2+}	7200	225.99 mg/g	15-20	-	[90]
$MnFe_2O_4$@TiO_2-rGO	Cu^{2+}	7200	118.45 mg/g	15-20	-	[90]
KP-FeNPs	Cr (VI)	7200	99.1%	20 – 90	5	[91]
Fe NPs	Pb (II)	-	97.5%	30-100	-	[92]
nZVI-NPs	lead	86400	79.33%	5 -10	4-8	[93]
Fe-NPs	chromium	16200	90%	10.6	4.7	[94]
Calcined-Fe/Pd NPs	As (Ⅲ)	1800	100%	30-60	6.2	[95]
nFeCu-CH	Cr (VI)	1800	97.1%	125	5	[96]
C–Fe/Ni NPs	arsenic (V)	-	87.3%.	-	-	[97]
FeNPs@HC	copper ions	-	95.24 mg/g	28 -196	-	[98]
Fe/Cu NPs	As (Ⅲ)	7200	8.5 mg/g	-	-	[99]
Fe/Cu NPs	As(Ⅴ)	7200	17.5 mg/g	-	-	[99]
Fe_3O_4@Ag	Hg^{2+} ions	-	99.40%	-	-	[100]
Cu_2O@LDH@Fe_3O_4	Cr (VI)	-	76.16 %	250	3	[101]
Fe_3O_4/NiO	Pb^{2+}	4800	97.65%	-	2-8	[102]
Fe_3O_4@ZnO	Cd (II)	-	99.81%	-	-	[103]
Fe_3O_4@ZnO	Pb (II)	-	99.76%	-	-	[103]
Fe_3O_4@ZnO	Cr (IV)	-	98.1%	-	-	[103]
TSA@ Fe_3O_4	As (III)	-	98%	-	-	[104]
TSA@ Fe_3O_4	As (V)	-	93%	-	-	[104
A- Fe_3O_4 NPs	As (V)	-	-	12	-	[105]
NiO– Fe_3O_4	Pb (II)	1800	100%	25-35	2-7	[106]
NiO– Fe_3O_4	Hg (II)	1800	99.71%	25-35	2-7	[106]
Fe_3O_4	Hg (II)	3600	99.2%	NCs:190, NPs:<10	7	[107]
Fe/Mn oxides	As (III)	129600	98%	1-20	4	[108]
Fe_3O_4@MgO	As(V)	120	99.9%	-	2-11	[109]
Fe_3O_4@MgO	F^-	1800	97.3%	-	2-11	[109]
$CoFe_2O_4$@SiO_2	Cd (II)	1800	350.08mg/g	-	6	[110]
PHPAm/Fe_3O_4@SiO_2-SH	Hg^{2+}	6900	256.41mg/g	-	6.11	[111]
PHPAm/Fe_3O_4@SiO_2-SH	Pb^{2+}	6360	227.27mg/g	-	6.48	[111]

The results also demonstrate that Fe_3O_4 NPs are particularly effective in removing Cu^{2+} ions compared to other forms of iron NPs, with a significant difference in removal efficiency. Additionally, the findings reveal that the highest efficiency for Cr (VI) removal by iron NPs occurs within a size range of 20–90 nm, with efficiency declining as nanoparticle size increases. Furthermore, removing As(III) by NPs sized 30–60 nm, with a reaction time of 30 minutes, exhibited the highest efficiency [105].

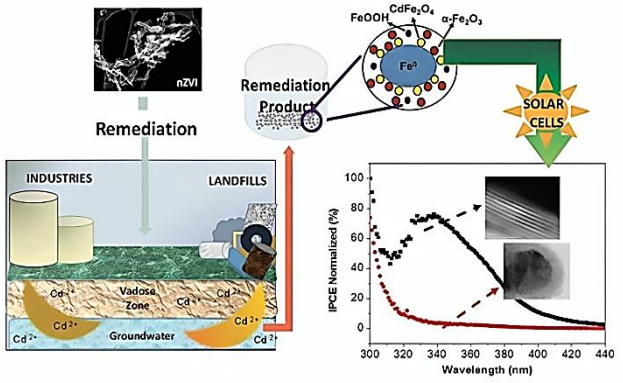

Fig. 5. The illustration of cadmium removal from water and its subsequent conversion into photo-electrochemical solar cells using nanoscale zero-valent iron [87].

3.3. Silver NPs

Ag NPs, or silver nanoparticles, are widely used for disinfecting water due to their antibacterial properties, which make them effective against a broad spectrum of bacteria, viruses, fungi, and diseases (Table 3). Ag NPs have been successfully immobilized on cellulose fibers in remediation tests, demonstrating antibacterial activity against Enterococcus faecalis, Escherichia coli, and inactivated bacterial suspensions within filtration systems. Additionally, Ag NPs synthesized via various chemical reduction methods have been incorporated into polyether sulfone (PES) microfiltration (MF) membranes, significantly reducing microbial activity on the membrane surfaces. These PES–Ag NP membranes exhibit strong antibacterial properties and great potential for wastewater treatment. Ag NPs effectively destroy pathogenic bacteria by inducing oxidative stress in cells, disrupting essential microbial processes, oxidizing vital components, and altering the structural integrity of the cell membrane. Given their ability to mitigate biofouling and purify sewage and wastewater, research on immobilizing Ag NPs on membranes and ceramic materials has gained significant traction over the past two decades. High-porosity filters composed of sawdust and clay are now employed to remove pathogens, including E. coli, from wastewater, thereby improving filtration efficiency. Advances in colloidal chemistry have further enhanced filter performance, with colloidal NPs achieving up to 97.8–100% removal of E. coli from wastewater [85, 112, 113].

Various types of Ag NPs, such as AgNPs-St-PEG-AcANCH, Fe_3O_4 @Ag@MESNa, XAg@C-TCZ, AgNPs/GO, and Ag NPs, have

Table 3. The purification of heavy metals in the ions form and mineral pollutants by ZVI NPs.

Type of NP	Contaminant removed	Contact time (s)	Removal efficiency	Size particle (nm)	pH	Ref.
AgNPs-St-PEG-AcANCH	Hg^{2+}	-	158.21 mg/g	-	7	[112]
AgNPs-St-PEG-AcANCH	Hg^{2+}	-	182.53 mg/g	-	6	[112]
Fe_3O_4@Ag@MESNa	Hg (II)	30s	100%	-	6.2	[85]
XAg@C-TCZ	Cr (VI)	7200	95.5%	-	-	[113]
AgNPs/GO	Fe (III)	1800	60-98%	33.64 -74.87	6	[115]
AgNPs/GO	Cr (VI)	4800	60-98%	33.64 -74.87	6	[115]
Ag NPs	chloride ion	72000	≥90%	-	-	[116]

demonstrated varying levels of efficiency and contact times in removing a range of pollutants, including Hg^{2+}, Cr (VI), Fe (III), and chloride ions. Each type exhibits distinct removal rates for specific pollutants. For example, AgNPs-St-PEG-AcANCH effectively removes Hg^{2+} with a removal capacity of 158.21 mg/g.

These NPs generate free radicals that attach to bacterial cell membranes, increasing membrane permeability and ultimately causing damage and apoptosis. Ag NPs also target DNA by interacting with its phosphorus and sulfur components, leading to further damage. Additionally, the breakdown of Ag NPs occasionally releases antimicrobial Ag^{+} ions, which bind to the thiol groups of essential enzymes, rendering them inactive and disrupting normal cellular functions. However, their long-term effectiveness is limited by their tendency to aggregate in liquid media, which reduces their antibacterial efficacy over time [85, 112, 113].

The illustration showcases the fabrication and functionality of a nanomembrane system enhanced with silver nanoparticles (Ag NPs). The schematic outlines the hybridization process, wherein polyvinyl chloride (PVC) is chemically modified with diamino pyridine (DAP) to produce a nanomembrane capable of incorporating Ag NPs. This modification enhances both the structural and functional properties of the membrane. The adsorption mechanism of heavy metal ions onto the membrane surface is also depicted. The embedded Ag NPs play a crucial role in boosting the adsorption process through mechanisms, such as electrostatic interactions, surface complexation, and chemical binding, thereby ensuring the efficient removal of heavy metal ions from water (Fig. 6). Ag NPs have been successfully immobilized on cellulose fibers in *in situ* remediation tests, demonstrating antibacterial activity against *Enterococcus faecalis, Escherichia coli,* and inactivated bacterial suspensions within filtration systems. Additionally, Ag NPs synthesized via various chemical reduction methods have been incorporated into polyether sulfone (PES) microfiltration (MF) membranes, significantly reducing microbial activity on the membrane surfaces. These PES–Ag NP membranes exhibit strong antibacterial properties and great potential for wastewater treatment.

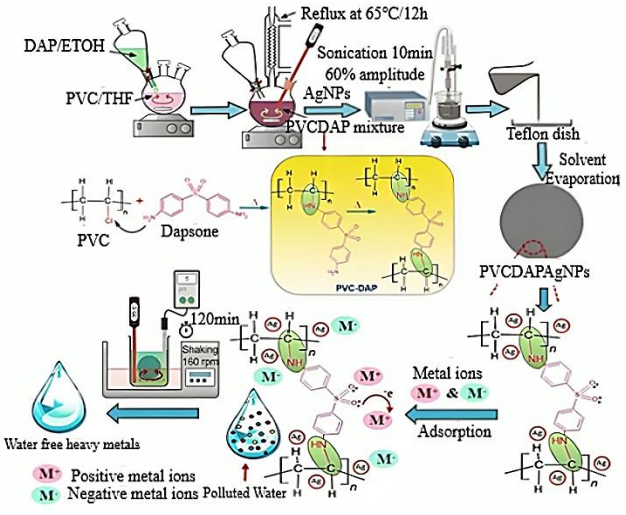

Fig. 6. The adsorption mechanism of heavy metal ions on membrane surfaces facilitated by Ag NPs [114].

Ag NPs effectively destroy pathogenic bacteria by inducing oxidative stress in cells, disrupting essential microbial processes, oxidizing vital components, and altering the structural integrity of the cell membrane. Given their ability to mitigate biofouling and purify sewage and wastewater, research on immobilizing Ag NPs on membranes and ceramic materials has gained significant traction over the past two decades. High-porosity filters composed of sawdust and clay are now employed to remove pathogens, including *E. coli,* from wastewater, thereby improving filtration efficiency. Advances in colloidal chemistry have further enhanced filter performance, with colloidal NPs achieving up to 97.8–100% removal of *E. coli* from wastewater [85,112,113]. Various types of silver NPs, such as AgNPs-St-PEG-AcANCH, Fe_3O_4 @Ag@MESNa, XAg@C-TCZ, AgNPs/GO, and Ag NPs, have demonstrated varying levels of efficiency and contact times in removing a range of pollutants, including Hg^{2+}, Cr (VI), Fe (III), and chloride ions. Each type exhibits distinct removal rates for specific pollutants. For example, AgNPs-St-PEG-AcANCH effectively removes Hg^{2+} with a removal capacity of 158.21 mg/g.

The size of Ag NPs, ranging from 33.64 to 74.87 nm for AgNPs/GO, can significantly influence the removal efficiency of inorganic pollutants. For materials, such as Fe_3O_4@Ag@MESNa, the pH of the environment, specifically at 6.2, plays a critical role in optimizing removal efficiency [85]. Similarly, the contact time with pollutants, such as 120 minutes for removing Cr (VI) using XAg@C-TCZ, directly affects removal performance. From the data presented in the table, it can be inferred that Ag NPs are an effective method for eliminating inorganic pollutants from aqueous solutions. Notably, removing Hg^{2+} achieves its highest efficiency at a pH of approximately 6. Likewise, in the case of Cr(VI) removal, shorter reaction times are associated with improved efficiency [115].

3.4. TiO_2 NPs

TiO_2 NPs have proven highly effective as photocatalysts in wastewater treatment due to their low toxicity to humans, excellent chemical stability, and ability to generate reactive oxygen species (ROS). They have been widely used as catalysts in ozonation processes, ensuring the complete mineralization of organic pollutants. Over the past two decades, there has been increasing interest in the potential of TiO_2 NPs to combat various viruses, including poliovirus 1, hepatitis B virus, herpes simplex virus, and MS_2 bacteriophages. The effective concentration of TiO_2 required to eliminate microorganisms from wastewater ranges from 0.1 to 1 g per liter, depending on light intensity and particle size. The generation of ROS, such as H_2O_2 and OH^- free radicals, during ultraviolet (UV)-A irradiation, plays a critical role in the reductive and oxidative processes responsible for the harmful effects of TiO_2 on microorganisms [90]. Table 1 presents a comparative analysis of the effectiveness of TiO_2 NPs in the treatment of mineral pollutants.

Fig. 2 illustrates the application of natural melanin/ TiO_2 hybrid materials for the simultaneous removal of dyes and heavy metal ions under visible light. These hybrid materials combine the biocompatibility and strong adsorption capabilities of natural melanin with the photocatalytic efficiency of titanium dioxide (TiO_2). Upon exposure to visible light, TiO_2 generates reactive species, such as hydroxyl radicals and superoxide ions, which effectively degrade organic dyes. Meanwhile, the active binding sites in melanin enhance the adsorption and immobilization of heavy metal ions. This synergistic mechanism enables efficient water treatment by addressing both organic and inorganic contaminants in a single, integrated process. Various types of titanium

dioxide (TiO_2) NPs have been extensively utilized to remove pollutants, such as Cu (II), Hg^{2+}, Pb^{2+}, and Cd^{2+}, with each variant demonstrating distinct removal efficiencies. For instance, core-shell $MnFe_3O_4$@TiO_2 NPs achieved a remarkable removal capacity of 225.99 mg/g for Cu (II), whereas TiO_2@MnO exhibited an 86.15% removal efficiency for Hg^{2+}.

The particle size of TiO_2 NPs is a critical factor influencing their performance, as evidenced by the 15–20 nm size range observed in core-shell $MnFe_2O_4$ @ TiO_2. Environmental pH significantly impacts the removal efficiency, with acidic conditions (pH ~4) enhancing the adsorption capacity for certain pollutants, such as Pb^{2+} [118]. Additionally, factors, such as contact time between the NPs and the pollutants are essential determinants of overall efficacy. Titanium dioxide NPs are widely employed for purifying inorganic contaminants from aqueous solutions due to their unique physicochemical properties. Notably, TiO_2 NPs exhibit optimal removal efficiency for Pb^{2+} under acidic conditions, particularly when their size ranges between 50 and 100 nm [119]. Furthermore, core-shell titanium-based NPs have demonstrated superior efficacy in removing Cu(II) ions [121].

3.5. Cerium Oxide NPs

Cerium oxide NPs, composed of cerium and oxygen atoms, are increasingly employed in applications, such as heavy metal removal and wastewater treatment due to their unique physicochemical properties. One of their most notable attributes is their catalytic ability to accelerate chemical reactions, particularly in the oxidation and removal of heavy metals from aqueous systems [122]. Table presents a comprehensive analysis and comparison of the efficacy of cerium oxide NPs in treating mineral pollutants.

Fig. illustrates the removal process of lead (II), chromium (VI), and cadmium (II) ions from water using cerium oxide NPs synthesized through a green and environmentally friendly method utilizing Pisum sativum (pea) pods. The biosynthesized NPs, characterized by their high surface area and abundant active sites, effectively adsorb and interact with heavy metal ions. The diagram emphasizes the role of cerium oxide NPs in binding and immobilizing these toxic ions, showcasing their potential as a sustainable and efficient solution for water purification. Additionally, the use of plant-derived materials underscores the eco-friendly nature of this approach, offering a cost-effective and greener alternative to conventional remediation technologies [123]. Various types of cerium oxide NPs, including Ce_xO_y, CuO/CeO_2, and CeO_2, have been employed to remove a range of pollutants, such as arsenic (As(V) and As (III)), cadmium (Cd), and chromium (Cr). These NPs exhibit differing levels of removal efficiency. For example, CexOy achieved a 95% efficiency in removing As (V), while CuO/CeO_2 demonstrated efficiencies of 89% and 93% in cadmium removal. The table also highlights the contact times with pollutant-containing solutions, which range from 15 to 30 minutes, depending on the specific application. The analysis underscores the significant potential of cerium oxide NPs for purifying inorganic pollutants from aqueous solutions, showcasing their high efficiency in pollutant removal. Notably, the highest removal efficiency for As (V) is consistently observed with various cerium oxide nanoparticle forms. Furthermore, the data suggests that for cadmium removal, the efficiency increases with decreasing nanoparticle size, reaching an optimal performance at a size of approximately 20 nm [123].

3.6. MnO NPs

Manganese dioxide NPs, due to their high specific surface area, are widely utilized for the removal of organic pollutants and heavy metals from water. When combined with magnetic compounds, their effectiveness in wastewater treatment is further enhanced under an external magnetic field. Additionally, manganese dioxide NPs can be integrated with other metal oxides to augment their activity. Dai et al. demonstrated superior performance in continuous and laminar flow experiments by synthesizing K-birnessite nanosheets on anatase nanofibers, which were employed to remove Congo red dye from aqueous solutions. Furthermore, γ- and α-MnO_2 nanostructures have shown significant efficacy in purifying water, effectively eliminating heavy metals and organic contaminants. Research has also highlighted the capability of manganese dioxide NPs in removing cadmium from aqueous systems, underscoring their potential as an advanced water purification material [128].

Fig. 4 illustrates the highly efficient removal of divalent heavy metals from aqueous systems using magnetically porous Fe_3O_4 - MnO_2 composites. This figure showcases the structure of the Fe_3O_4-MnO_2 composite, which synergistically combines the magnetic properties of Fe_3O_4 NPs with the high adsorption capacity of MnO_2. The interaction between metal ions and the surface of the composite material is emphasized, demonstrating its effectiveness in adsorbing and removing heavy metals from aqueous solutions [129].

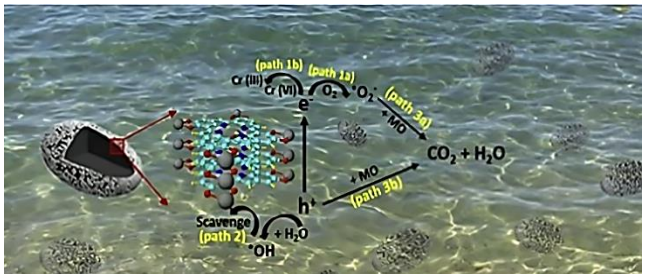

Fig. 7. Melanin/TiO_2 hybrid materials for efficient removal of dyes and heavy metal ions under visible light [117].

Table 4. The purification of heavy metals in the ions form and mineral pollutants by TiO_2 NPs.

Type of NP	Contaminant removed	Contact time	Removal efficiency	Size particle	pH	Ref.
core-shell $MnFe_2O_4$@TiO_2	Cu (II)	120min	225.99 mg/g	15-20 nm	-	[90]
MnFe2O4@TiO_2-rGO	Cu (II)	120min	118.45 mg/g	15-20 nm	-	[90]
TiO_2@MnO	Hg^{2+}	-	86.15%	25 nm	7	[118]
MC/ TiO_2	Pb^{2+}	-	98%	50 and 100 nm	4	[119]
TiO_2	Pb^{2+}	-	82.53%	18 nm	7.6	[120]
TiO_2	Cd2+	24h	80%	4.40nm	7	[121]

Table 5. The purification of heavy metals in the ions form and mineral pollutants by Cerium oxide NPs.

Type of NP	Contaminant removed	Contact time	Removal efficiency	Size particle	pH	Ref.
Ce_xO_y	As(V)	20 min	95 %	-	-	[122]
CuO/CeO_2	Cd	-	89%	15.45nm	-	[124]
CuO/CeO_2	Cd	-	93%	16.79nm	-	[124]
CeO_2	Cr	15min	93%	-	-	[125]
CeO_2	Cd	15min	89%	-	-	[125]
CeO_2	As (III)	20min	35.28mg/g	-	3-11	[126]
MCO	As(V)	30min	95%	-	3	[127]

Fig. 8. The removal of Pb(II), Cr(VI), and Cd(II) Ions from Water Using Green-Synthesized Cerium Oxide NPs derived from Pisum sativum Pods [123].

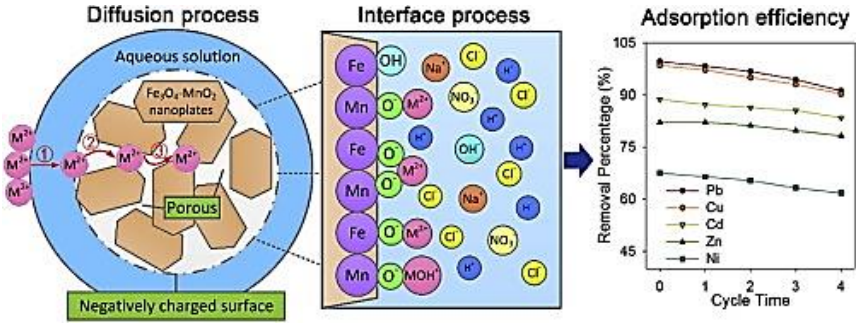

Fig. 9. The highly efficient removal of bivalent heavy metals from aqueous systems using magnetic porous Fe_3O_4-MnO_2 [129].

Table 3 highlights the effectiveness of manganese oxide NPs in treating mineral pollutants. Various types, including core-shell $MnFe_2O_4@TiO_2$, $MnFe_2O_4@TiO_2$-rGO, Fe/Mn oxides, Mnp-FeMn, and MnO, have been utilized to remove contaminants, such as Cu(II), Hg^{2+}, As (III), and As (V). These NPs exhibit varying degrees of efficiency in pollutant removal. For example, core-shell $MnFe_2O_4@TiO_2$ achieved a high removal capacity of 225.99 mg/g for Cu (II), whereas $MnFe_2O_4@TiO_2$-rGO demonstrated a removal rate of 118.45 mg/g for the same pollutant. In conclusion, manganese oxide NPs present a promising solution for removing inorganic pollutants from aqueous solutions. Notably, the removal efficiency for As (V) and As (III) reaches its maximum when the reaction time is prolonged, and the pH is maintained within the optimal range of approximately 4. This underscores the importance of reaction parameters in optimizing pollutant removal using manganese oxide-based nanomaterials.

3.7. MgO NPs

Magnesium NPs are critical in nanotechnology, particularly in water and wastewater treatment. Their high surface area and reactivity make them effective adsorbents for heavy metals and pollutants, contributing significantly to purification processes [131]. Table 7 illustrates the application of silica-based magnesium oxide (MgO) and nickel oxide-magnesium oxide (NiO-MgO) NPs in treating mineral pollutants, highlighting their potential to improve water quality and addressing environmental challenges.

Fig. 5 illustrates the efficient and rapid removal of heavy metal ions, Pb (II) and Cu (II), from aqueous solutions using MgO nanorods. The figure highlights the structural and morphological characteristics of the nanorods, including their high surface area and abundance of active sites, which enhance the adsorption of heavy metal ions. It also depicts the adsorption mechanism, demonstrating the interaction between positively charged metal ions and the negatively charged or reactive sites on the MgO nanorods. Comparative analysis demonstrates that these NPs are highly effective in removing various pollutants, including Zn^{2+}, Cu^{2+}, Cr^{3+}, As(V), and F^{-}. MgO and NiO-MgO NPs exhibit varying removal efficiencies for different contaminants. For example, MgO NPs achieved a high efficiency of 546.45 mg/g in removing Cu^{2+}, whereas NiO-MgO NPs reached an efficiency of 209.51 mg/g for Cr^{3+} removal. Overall, the research highlights the effectiveness of silica-based magnesium oxide and nickel oxide-magnesium oxide NPs in purifying water by efficiently removing a range of pollutants from aqueous solutions. Notably, the results indicate that the removal efficiency of Cu^{2+} is higher when using individual MgO NPs compared to their composite state.

3.8. SiO_2 NPs

As shown in Table 4, these NPs have a wide range of applications across various industries due to their unique properties.

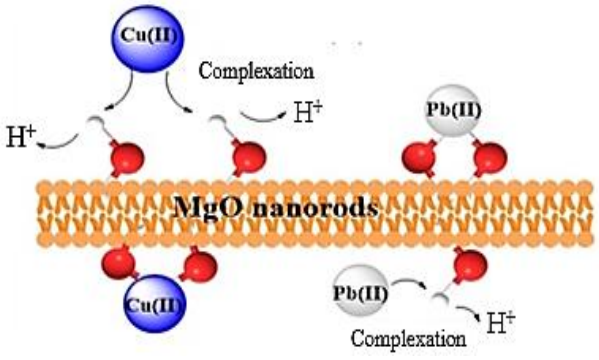

Fig. 10. The efficient and rapid adsorption of Pb(II) and Cu(II) ions from aqueous solutions using MgO nanorods [132].

Table 6. The purification of heavy metals in the ions form and mineral pollutants by MnO NPs.

Type of NP	Contaminant removed	Contact time	Removal efficiency	Size particle	pH	Ref.
core-shell $MnFe_2O_4$@TiO_2	Cu (II)	120min	225.99 mg/g	15-20 nm	-	[90]
$MnFe_2O_4$@TiO_2-rGO	Cu (II)	120min	118.45 mg/g	15-20 nm	-	[90]
TiO_2@MnO	Hg^{2+}	-	86.15%	25 nm	7	[118]
Fe/Mn oxides	As (III)	36h	98%	1-20nm	4	[108]
MNp-FeMn	As (III)	12h	71%	8.72	6.50	[128]
MNp-FeMn	As (V)	12h	72%	8.72	6.50	[128]
MNp	As (V)	12h	54%	8.19	6.11	[128]
MNp	As (III)	12h	63%	8.19	6.11	[128]
MnO	As	-	96 %	2.33-15.20nm	4	[130]

Table 7. The purification of heavy metals in the ions form and mineral pollutants by MgO NPs.

Type of NP	Contaminant removed	Contact time	Removal efficiency	Size particle	pH	Ref.
NiO–MgO silica-based nanoparticles	Zn^{2+}	30-60 min	37.69 mg/g	-	7-11	[131]
NiO–MgO silica-based nanoparticles	Cu^{2+}	30-60 min	69.68 mg/g	-	7-11	[131]
NiO–MgO silica-based nanoparticles	Cr^{3+}	30-60 min	209.51mg/g	-	7-11	[131]
MgO	Cu^{2+}	-	546.45mg/g	50 nm	-	[133]
Fe_3O_4@MgO	As(V)	2min	99.9%	-	2-11	[109]
Fe_3O_4@MgO	F^-	30min	97.3%	-	2-11	[109]

Table 8. *The purification of heavy metals in the ions form and mineral pollutants by SiO_2 NPs.*

Type of NP	Contaminant removed	Contact time	Removal efficiency	Size particle	pH	Ref.
Superparamagnetic Fe_3O_4@SiO_2@GLYMO(S)-en	Pb^{2+}	55min	93.5 mg/g	-	-	[88]
Superparamagnetic Fe_3O_4@SiO_2@GLYMO(S)-en	Cd^{2+}	55min	80.64 mg/g	-	-	[88]
$CoFe_2O_4$@SiO_2	Cd (II)	30min	350.08mg/g	-	6	[110]
PHPAm/Fe_3O_4@SiO_2-SH	Hg^{2+}	115min	256.41mg/g	-	6.11	[110]
PHPAm/Fe_3O_4@SiO_2-SH	Pb^{2+}	106min	227.27mg/g	-	6.48	[111]
SiO_2	Cd (II)	2h	32.2 mg/g	37.7 nm	6-8	[134]
SiO_2	Pb (II)	2h	42.2 mg/g	37.7 nm	6-8	[134]
pSiO_2-NH_2	Cr (VI)	2h	97%	80-200 nm	1	[135]
SiO_2	Cd^{2+}	24h	Removal efficiency	5.05 nm	7	[121]

SiO_2 NPs, for instance, serve as catalyst supports in numerous chemical processes. Their high surface area and porosity make them highly effective for attaching catalytic species, thereby enhancing the efficiency of catalytic reactions. Additionally, SiO_2 NPs play a significant role in wastewater treatment and water purification processes, contributing to environmental remediation. By acting as adsorbents, they effectively remove organic pollutants and heavy metals from water sources [134]. Fig. 11 shows the effect of the magnetic core size of amino-functionalized mesoporous Fe_3O_4 core-shell SiO_2 NPs on the removal efficiency of heavy metal ions. It depicts the relationship between core size and adsorption capacity and shows how changes in core size affect the magnetic properties, surface area, and distribution of functional amino groups [135].

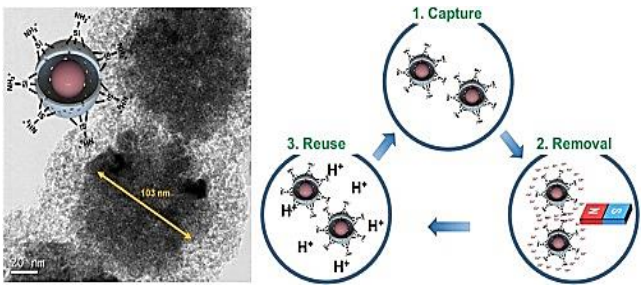

Fig. 11. *The impact of magnetic core size in amino-functionalized Fe_3O_4 - mesoporous SiO_2 core-shell NPs on the removal efficiency of heavy metal ions [135].*

Referring to table 4, in the context of treating mineral pollutants with SiO_2 NPs, it is clear that these NPs have been employed in various methods for removing contaminants, such as Pb^{2+}, Cd^{2+}, Cr (VI), and Cd (II). SiO_2 NPs have consistently demonstrated their effectiveness in water purification, with favorable outcomes influenced by particle size, pH, and interaction time. The table indicates that the removal efficiency for Pb^{2+} as part of a composite system improves with longer reaction times, whereas the removal efficiency for Cd^{2+} as a composite, increases with shorter reaction times. However, when silicon oxide NPs are used in their singular form, the removal efficiency for both ions decreases as the reaction time increases.

4. The role of nanoparticles in removing metals from wastewater

The discharge of various contaminants in wastewater, including organic and inorganic pollutants, such as dyes, herbicides, personal care products, and heavy metals, is primarily driven by population growth and rapid industrialization. A significant concern is the direct release of partially treated or untreated wastewater into surface water bodies, posing severe environmental risks. This not only threatens aquatic life but also disrupts the food chain and ultimately impacts human health through bioaccumulation and bio-magnification. Recently, eco-friendly nanomaterials have been developed to effectively remediate and eliminate harmful toxins, with ongoing advancements in this field. Various NPs with different sizes, chemical properties, and morphologies have been engineered for remediation purposes. These NPs operate through four primary mechanisms: adsorption, filtration,

transformation, and catalysis, enabling efficient removal or degradation of contaminants [71, 97, 130].

Pollutants adhere to the surface of the adsorbent through chemical or physical interactions in a process known as adsorption (Fig.-a). The typical adsorption process for wastewater treatment and pollutant removal occurs in three phases: (i) transport of the contaminant to the adsorbent's surface, (ii) binding of the contaminant at the surface, and (iii) diffusion within the adsorbent. NPs are particularly effective adsorbents due to their large specific surface areas, which make them easy to functionalize for targeting specific pollutants. Additionally, the nanoscale pores on NP surfaces further enhance their ability to adsorb contaminants, improving the overall efficiency of the remediation process [74, 85, 86].

Filtration plays a critical role in the treatment of water and wastewater (Fig.-b). Nano-filtration, a membrane separation technology, incorporating NPs, has gained significant attention due to its high penetration rate and operational efficiency under pressure. Unlike reverse osmosis, which operates under pressures ranging from 20 to 100 atm, nano-filtration requires lower pressures (7–30 atm) and features a consistent surface charge, enhancing its selectivity toward specific pollutants. Environmental pollution results from various human activities, necessitating effective remediation strategies. Oxidation and reduction (redox) processes have been shown to efficiently eliminate both organic and inorganic contaminants from water and wastewater (Fig.-c). These redox reactions influence the speciation of metals in wastewater, thereby reducing their toxicity. Additionally, these processes can stabilize metals in a less toxic oxidation state, further mitigating environmental risks [74, 85, 86].

Catalysis technology, leveraging NPs, offers an affordable and efficient method for eliminating pollutants from water and wastewater. By utilizing inexpensive and readily available raw materials, highly effective catalysts can be developed. Among these catalytic approaches, photocatalysis stands out as a key method for accelerating the degradation of inorganic pollutants. In photocatalysis, NPs serve as a light-activated catalytic medium, facilitating the breakdown of various contaminants in wastewater. When light energy exceeding the bandgap energy of a semiconductor catalyst is absorbed, electron-hole (e-h) pairs are generated. These pairs initiate the formation of highly reactive oxidizing and reducing agents, including radicals, such as OH^- and O_2^-, which effectively degrade pollutants in the wastewater (Fig.-d) [74, 85, 86].

4.1. Mechanisms of heavy metal adsorption by metallic nanoparticles

4.1.1 Physical adsorption

Physical adsorption is one of the primary mechanisms for removing heavy metals using metallic NPs. In this process, metal ions are non-chemically adsorbed onto the nanoparticle surface through van der Waals or electrostatic forces. The high surface area and abundant active sites of NPs enable efficient interaction with metal ions in wastewater. This mechanism is influenced by several factors, including nanoparticle size, surface charge, the pH of the medium, and the concentration of metal ions [136,137]. For example, in alkaline environments where NPs often carry a negative surface charge, the adsorption of positively charged metal ions, such as Pb^{2+} and Cd^{2+}, significantly increases. Conversely, in acidic conditions, H^+ ions compete with metal ions for adsorption sites, reducing adsorption efficiency. One major advantage of physical adsorption is its reversibility: adsorbed metal ions can be released by altering environmental conditions, such as lowering the pH, which facilitates nanoparticle recovery [138]. A practical application of this mechanism can be seen with Fe_3O_4 NPs for cadmium and lead adsorption. These NPs, owing to their magnetic properties, can be easily recovered and reused. Physical adsorption is often used as an initial step, complementing other mechanisms, to achieve higher heavy metal removal efficiency [139].

4.1.2. Chemical adsorption

Chemical adsorption represents a more advanced mechanism compared to physical adsorption; wherein metal ions bind to NPs through the formation of chemical bonds with functional groups present on the nanoparticle surface. Functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and thiol (-SH), either naturally occurring or chemically modified on the nanoparticle surface, are essential for this process. These chemical bonds are significantly stronger than the physical interactions seen in physical adsorption, resulting in a more stable and permanent binding of metal ions to the NPs [140]. Several factors influence chemical adsorption, including the type of heavy metal, the specific functional groups involved, the pH of the environment, and the concentration of metal ions. For instance, ZnO NPs functionalized with sulfur groups have demonstrated a remarkable ability to adsorb mercury ions (Hg^{2+}) by forming strong covalent bonds. Under controlled laboratory conditions, these NPs effectively removed mercury ions from aqueous solutions to trace levels [141].

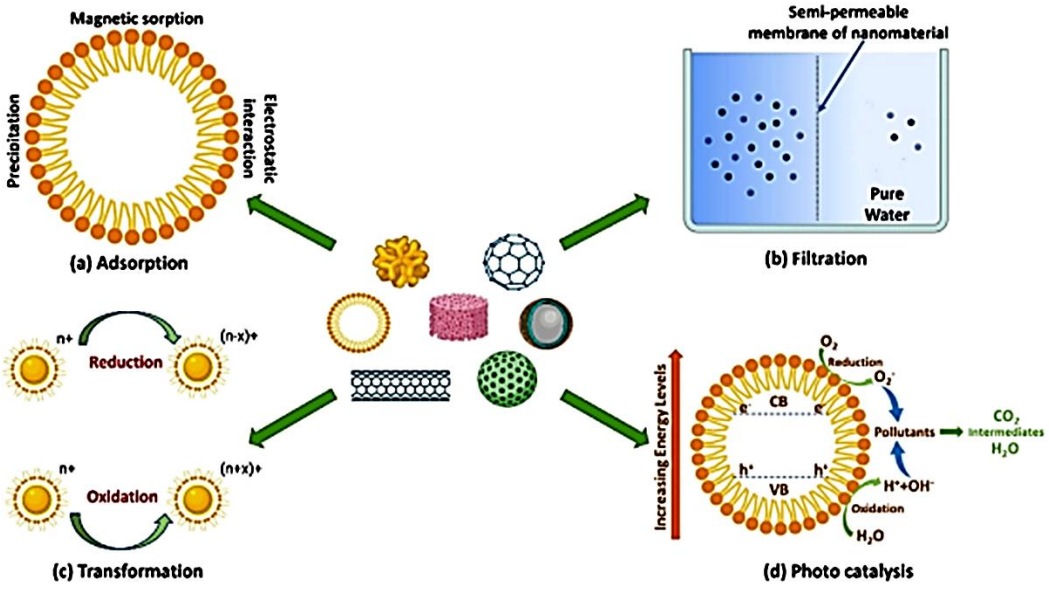

Fig. 12. The various mechanisms of contaminant removal facilitated by NPs: (a) Adsorption, (b) Filtration using semi-permeable membranes embedded with NPs, (c) Redox reactions for contaminant degradation, and (d) Pollutant removal via photocatalysis. In the photocatalytic process, CB represents the Conduction Band, VB denotes the Valence Band, (e) signifies electron, and (h) represents hole [86].

A notable advantage of chemical adsorption is its high selectivity. Functional groups can be tailored to target specific heavy metals, enhancing the efficiency of the removal process. For example, NPs modified with thiol (-SH) groups are particularly effective at adsorbing soft heavy metals, namely mercury due to the strong affinity between sulfur and mercury. This selectivity makes chemical adsorption a critical mechanism for water treatment systems, especially in scenarios where pollutant concentrations are extremely low [142].

4.1.3. Redox reactions

Redox reactions represent an advanced mechanism for heavy metal removal using metallic NPs. In this process, NPs function as reducing agents, transforming toxic metal ions into less harmful, lower oxidation states. For instance, highly toxic and carcinogenic chromium (VI) is reduced to less toxic chromium (III) through the use of zero-valent iron nanoparticles (ZVI NPs) [144]. This mechanism is highly effective due to the electron-donating capabilities of NPs, particularly metallic ones, such as iron and zinc. When exposed to water and oxygen, NPs release electrons that directly engage in reducing metal ions. One significant advantage of this method is its rapid reaction rate and adaptability to diverse environmental conditions [145]. Studies indicate that redox reactions proceed faster in acidic environments because the presence of additional protons enhances the reduction process. For example, iron NPs have successfully reduced chromium (VI) in industrial wastewater to its less toxic form [146]. This mechanism not only eliminates harmful pollutants from water but also transforms them into environmentally safer compounds, which is a vital advantage for sustainable environmental management.

4.2. Mechanisms of dye adsorption by metallic nanoparticles

4.2.1. Electrostatic Interaction

Electrostatic interaction is a key mechanism for removing dyes from wastewater, relying on the electrical charge interactions between NPs and dye molecules. Dye molecules typically carry either positive or negative charges, which interact with oppositely charged NPs [148]. The surface charge of NPs plays a pivotal role in this mechanism and is strongly influenced by PH. For instance, TiO_2 NPs develop a positive surface charge in acidic environments, making them highly effective for adsorbing anionic dyes, such as methyl orange. Conversely, in alkaline conditions, the surface charge of the NPs becomes negative, enhancing their capacity to adsorb cationic dyes, namely methylene blue [149]. Research has shown that electrostatic adsorption is particularly efficient for charged dyes, and its combination with other mechanisms, such as photocatalytic degradation, can further enhance wastewater treatment performance. This mechanism is adaptable and efficient, given its pH-dependent nature and the ability to modulate nanoparticle surface charges [150].

4.2.2. Photocatalytic Degradation

Photocatalytic degradation is an advanced method for removing dyes from wastewater using metallic NPs, such as ZnO and TiO_2. When exposed to light, these NPs generate electron-hole pairs, producing reactive free radicals, namely OH^- and O_2^-. These radicals react with dye molecules, breaking them into harmless byproducts, such as CO_2 and H_2O [150]. A notable advantage of this mechanism is its non-selectivity, allowing the degradation of virtually all dyes, regardless of their chemical structure. For example, ZnO NPs have been shown to degrade rhodamine B dye under UV-light exposure completely. Photocatalytic degradation efficiency depends on several factors, including light intensity, exposure time, and nanoparticle concentration [152]. This mechanism not only effectively removes dyes from wastewater but also breaks down their complex chemical structures into simpler, non-toxic components. As a result, photocatalytic degradation is widely recognized as a sustainable and environmentally friendly solution for treating dye-contaminated wastewater.

5. Concluding Remarks

NPs have emerged as a revolutionary tool for wastewater treatment, offering superior efficiency in removing organic and inorganic pollutants. This review has highlighted the diverse applications of metal-based NPs, including zinc, iron, silver, titanium dioxide, cerium oxide, manganese oxide, and magnesium oxide, in tackling heavy metals, dyes, and microbial contaminants. Their multifunctionality—encompassing adsorption, filtration, catalysis, and redox reactions—positions NPs as a promising solution for mitigating water pollution. Key findings demonstrate that nanoparticle size, surface charge, pH, and interaction time significantly influence removal efficiency. Innovations, namely hybrid nanocomposites and functionalized surfaces have further enhanced selectivity and performance, paving the way for eco-friendly and scalable water treatment systems. Moreover, photocatalysis and redox mechanisms have shown exceptional potential for degrading complex pollutants into non-toxic byproducts, thereby addressing challenges of bioaccumulation and environmental persistence. Despite their transformative potential, challenges persist regarding nanoparticle toxicity, environmental safety, and large-scale implementation. Future research should focus on developing green synthesis methods, optimizing cost-effectiveness, and conducting long-term studies on environmental impacts. Integrating nanotechnology with advanced treatment systems, such as membrane filtration and advanced oxidation processes, holds immense promise for achieving sustainable wastewater management. In conclusion, nanotechnology offers a cutting-edge approach to addressing global water scarcity and pollution, emphasizing the need for interdisciplinary collaboration to translate laboratory success into real-world applications. By leveraging the unique properties of NPs, the path toward efficient, sustainable, and scalable water purification is increasingly within reach.

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Credi authorship contribution statement

- Amir Mabudi: Administration, Conceptualization, Methodology, Writing – Review & Editing.
- Meysam Naseri: Writing–Original Draft, Writing – Review & Editing.
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