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Research Article

Nanoparticle-Based Adsorbents for the Removal of Heavy Metals and Organic Pollutants: Recent Advances and Future Prospects

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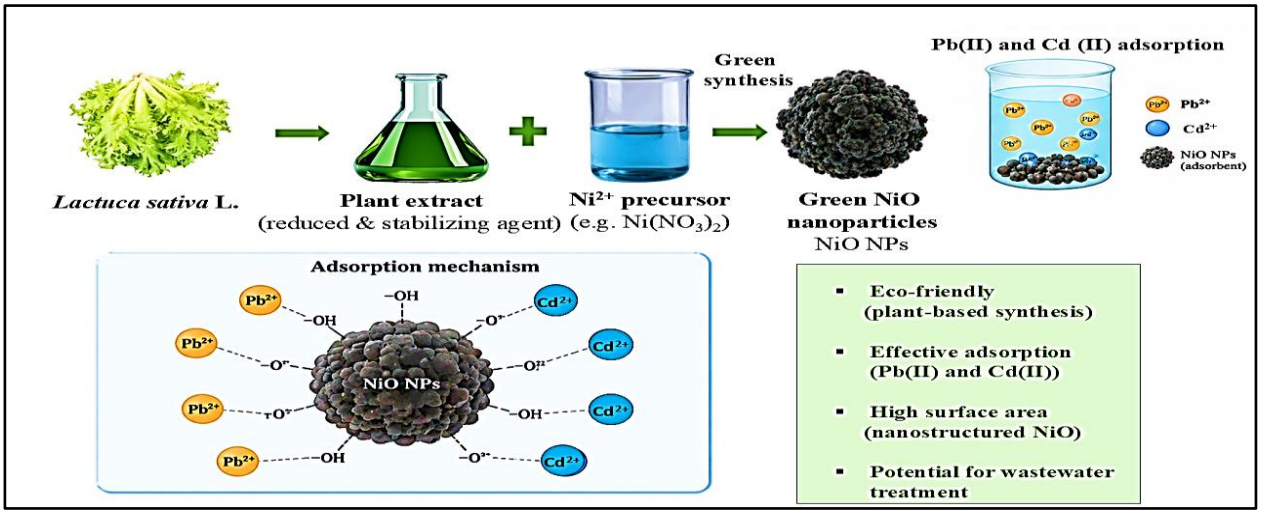
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Abstract

The growing emissions of heavy metals and organic contaminants from industries, agriculture, mining, and households have presented great challenges for water and wastewater treatment. The use of adsorbents based on nanoparticles has become attractive compared with traditional adsorbents owing to their large surface area, variable surface chemistry, numerous active sites, and feasibility of magnetic separation. This review article critically evaluates recent developments in metal oxide nanoparticles, carbonaceous nanomaterials, magnetic nanoparticles, and nanocomposites in the adsorption of heavy metals and organic contaminants from aqueous solutions. Some recent findings have shown high adsorption capacity with 897.0, 437.5, and 354.3 mg g^{-1} for Pb^{2+}, Cu^{2+}, and Cd^{2+}, respectivelyThe adsorption capacity of GO-ZrATMP was found to be 373, 320, and 281 mg g^{-1} for Pb^{2+}, Cd^{2+}, and Hg^{2+} ions, whereas that of modified graphene oxide was 370.0, 136.2, and 109.6 mg g^{-1} for Hg^{2+}, Cr (VI), and Pb^{2+} ions, respectively. In the case of organic pollutants, the adsorption capacities of IDA-GO@Fe_3O_4 were 437.10 mg g^{-1} for methylene blue, while those of MgFe-LDH·Fe_3O_4 and sugarcane-bagasse cellulose/GO were 153.2 and 143.29 mg g^{-1} for diclofenac and atrazine, respectively. Important mechanisms involved in adsorption include surface complexation, electrostatic interactions, ion exchange, chemisorption, and physisorption. Although laboratory efficiency is extremely high, issues like agglomeration, leaching, toxicity, regeneration, reproducibility, affordability, and scalability persist.

Keywords: Nanoadsorbents, Heavy metals, Organic pollutants, Nanocomposites, Wastewater treatment

Graphical Abstract



1. Introduction

Industrialization, urbanization, mining, agriculture, and chemical industries have resulted in increasing pollution with inorganic and organic pollutants, leading to ongoing water quality issues[1]. Inorganic pollutants, including Pb, Cd, Cr, Hg, As, Ni, Cu, and Zn, are major pollutants owing to their toxicity, persistence, resistance to degradation, and bioaccumulation [2]. Biodegradable pollutants are easily biodegradable, unlike heavy metals, which are not easily degraded by biological activities [3]. Polluted waters in the mining industry, metal industry, electroplating, and manufacturing contain multiple types of heavy metal ions[1]. Organic pollutants in industrial wastewater include dyes, drugs, pesticides, phenolic compounds, etc.[4].

These two together add complexities to the process of treatment as the chemicals vary in composition, charge, solubility, and attraction to treatment material [2]. Industrial wastewaters contain many synthetic dyes, which pose a risk to aquatic ecosystems due to their stability and resistance to biological treatment [5]. Thus, there is a need for treatment materials that can deal with various types of pollutants under complicated aqueous conditions [6].

Traditional approaches to wastewater treatment might be efficient in dealing with certain contaminants; however, their efficacy may be limited by complicated pollutant mixtures and low contaminant concentrations [6]. Adsorption technology has been attracting more interest because of its efficiency and universal applicability [2]. The efficiency of the adsorption process depends largely on the characteristics of the adsorbent material, such as its surface properties, functional groups, porosity, and active sites [6].

Adsorbents developed using nanoparticles have evolved as superior materials owing to the increased surface area offered by the tiny particles[5]. Metal oxides, zero-valent metals, carbon nanomaterials, graphene oxide materials, magnetic nanoparticles, MOFs, and nanocomposites have thus been explored for heavy metal removal and organic pollutants [2]. Surface functionalization can further increase the interaction between the pollutant and adsorbent, increasing selectivity and adsorption efficiency[7]while magnetic nanocomposites make adsorbent separation easy after treatment[8].

Nanocomposites can utilize the properties of various materials, which enhances their surface function and pollutant removal capabilities [4]. Nonetheless, the problems of nanoparticle aggregation, difficulty in recovery, leaching, regeneration, and environmental safety continue to pose serious challenges (18). Therefore, future research on nanoadsorbents must consider their adsorption efficiency, as well as their regeneration, recyclability, stability, safety, and scalability[2]. This paper analyzes current trends in nanoparticle-based adsorbents that are used to remove heavy metals and organic contaminants from water and wastewater through metal oxides, magnetic nanoparticles, carbon-based materials, graphene-based materials, MOFs, and multifunctional nanocomposites[2].

Emphasis is made on adsorption processes such as electrostatic, ion exchange, surface complexation, chemisorption, physisorption, and functional group interactions [5]. Comparison of their efficiency is based on the type of pollutant, adsorption capacity, operation parameters, kinetics, isotherms, and regeneration ability [6]. Nanocomposite fabrication, stability, leaching, toxicity, regeneration, practical application in real wastewaters, economic viability, and scale-up aspects are further considered in this review [1], [8]. Finally, future research aspects are outlined in terms of sustainable synthesis, multifunctional nanoadsorbents, real wastewater applications, recyclability, and environmentally friendly nanomaterials [2].

2. Nanoparticle-Based Adsorbents

2.1 Metal Oxide Nanoparticles

Metal oxide nanoparticles offer great promise as adsorbents because the small size of these particles allows them to have highly reactive surfaces that enable high interaction with contaminants present in the solution [9]. MnO_2 nanoparticles present a good choice for removing metals because of their ability to interact effectively with dissolved metal ions even in acidic environments [10]. In a study carried out on acid mine drainage, ε-MnO_2 was found to adsorb 172.14 mg g^{-1} Pb^{2+} at pH 2 [10].

Moreover, the same investigation showed that Pb^{2+} adsorption was accomplished by ion-exchange reactions linked with the dissolution and surface complexation processes related to Mn^{2+}. It demonstrated how adsorption may include not only the surface reaction but also the dissolution process [10]. Another MnO_2-based material was synthesized through the synthesis of MnO_2 and Fe_3O_4 in alginate/carboxymethyl-cellulose beads, thus obtaining a magnetic adsorbent suitable for selective removal of Tl(I) ions [11]. These MnO_2-doped magnetic beads provided an adsorption capacity of 38.8 mg g^{-1} of Tl(I) ions and close to 100% removal efficiency of Tl(I) with high selectivity towards the competing ions [11]. Metal oxides can be combined with naturally available biomass to unite the nanoscale reactivity of metal oxides with the features of renewable matrices [12]. In particular, MnO_2-functionalized Salicornia europaea biomass proved its ability to have a breakthrough adsorption capacity of 251.16 mg g^{-1} for Pb^{2+} [12].

2.2 Carbon-Based Nanomaterials

There are a variety of carbon-based nanomaterials such as graphene oxide (GO), reduced graphene oxide (rGO), carbon nanotubes (CNTs), and carbon nanofibers (CNFs) that have been extensively studied as adsorbents due to their high specific surface area and modifiable surface properties [13]. The presence of oxygenated groups in graphene oxide creates active sites for interaction with metal ions and organic pollutants present in aqueous media. It was observed that graphene oxide nanosheets effectively removed pharmaceutical compounds from aqueous solutions [14]. The adsorption capacity of graphene-based nanomaterials can be improved through surface modification; violuric acid-functionalized reduced graphene oxide was highly effective in removing Hg^{2+}, Pb^{2+} , and As^{3+} [15].

Carbon nanotubes also offer additional adsorption sites on account of their graphitic surfaces, which may be oxidized chemically to create functional groups that improve binding interactions with metal ions. In a study carried out by Li et al. (2024), it was established that oxidized multiwalled carbon nanotubes offered improved adsorption of Pb(II) and Cd(II).

Carbon nanofibers may also be used as substrates for biological and chemical functionalization; this is evidenced in a study where an Enterococcus faecalis/CNF composite was able to attain an adsorption capacity of 255 mg g^{-1} for As (III) [16].

2.3 Magnetic Nanoparticles

Magnetic nanoparticles such as those based on Fe_3O_4 are promising adsorbents because the magnetic separation technique enables the separation of the adsorbent from the treated wastewater without traditional filtration or centrifugation [17]. The surface modification of magnetic nanoparticles can increase the affinity towards the targeted contaminant; for instance, the functionalization of Fe_3O_4-based nanomaterials resulted in the efficient removal of heavy metals via the interaction with surface functional groups [17]. The magnetic adsorbents may be coupled with carbonaceous material to merge the high capacity of carbon with the convenience of magnetic separation. The magnetic carbon nanocomposite synthesized from carbon obtained from biomass had a high efficiency in the removal of Pb, Cu, and Cr (VI) ions and could retain its performance

even after multiple reuse [18]. Moreover, magnetic carbon was examined for the removal of pharmaceutical waste, and the synthesis of magnetic iron oxide nanoparticles in the activated carbon allowed adsorption and magnetic separation/regeneration of the adsorbate [19].

2.4 Nanocomposites

Nanocomposites involve the combination of two or more materials to achieve complementary physicochemical property in a bid to overcome the challenges related to individual nanoadsorbents [20]. The use of Fe_3O_4/graphene oxide/chitosan nanocomposites that combine the adsorption properties of GO and chitosan together with the magnetic separation properties of Fe_3O_4 resulted in a maximum Pb(II) adsorption capacity of 63.45 mg g^{-1} [17]. Other nanocomposites that have been used for the simultaneous removal of Ni^{2+} and Cd^{2+} ions using GO-CuO nanocomposites achieved removal efficiencies of approximately 89.6% and 97.1%, respectively (Table 1), when the system was optimized through batch experiments. A tertiary magnetic nanocomposite of GO that contains chitosan or polyaniline has also been used for the simultaneous adsorption of Cr(VI) and Pb(II) ions, where the polyaniline-based nanocomposite was able to achieve adsorption capacities of 111.7 mg g^{-1} for Cr(VI) and 118.44 mg g^{-1} for Pb(II) [18]. Hydrogel beads composed of graphene oxide, magnetic iron oxide (Fe_3O_4), MOFs, and alginate have been developed to achieve the removal of various pharmaceutical contaminants along with magnetic separation and regeneration [21].

Table 1. Representative nanoadsorbents for heavy-metal removal and their adsorption performance.

Nanoadsorbent category	Materials	Functional feature	Target pollutant(s)	Applications	Main advantage	Reference
Metal oxide	Hollow mesoporous MnO_2	Hollow mesoporous structure with abundant adsorption sites	Pb^{2+}, Cu^{2+}, Cd^{2+}	qmax = 897.0, 437.5 and 354.3 mg g^{-1} for Pb, Cu and Cd, respectively	High heavy-metal uptake and structural stability	[9]
Metal oxide	Green Fe_3O_4/iron oxide NPs	Plant-mediated synthesis; magnetic iron-oxide surface	Cd^{2+}, Ni^{2+}	Cd^{2+}: 78 and 74 mg g^{-1}; Ni^{2+}: 64.8 and 80 mg g^{-1} for the two plant-derived materials	Green synthesis and magnetic recovery potential	[22]
Metal oxide	Green NiO NPs	Plant-extract-mediated NiO synthesis	Pb^{2+}	99.99% removal under optimized conditions; qmax = 60.13 mg g^{-1}	High Pb removal and green preparation	[23]
Magnetic nanomaterial	$CoFe_2O_4$@SiO_2 –NH_2	Magnetic ferrite core with silica and amino functionalization	Pb^{2+}, Cu^{2+}, Zn^{2+}	qmax = 254.453, 277.008 and 258.398 mg g^{-1} for Pb, Cu and Zn	Magnetic separation plus amino-metal coordination	[24]
Carbon-based nanomaterial	GO–Zr–ATMP composite	GO surface modified with Zr and phosphonate groups	Pb^{2+}, Cd^{2+}, Hg^{2+}	qmax = 373, 320 and 281 mg g^{-1}, respectively	High capacity and simultaneous multi-metal separation	[25]
Chitosan-based magnetic nanocomposite	TPP-CMN	Fe_3O_4 coated with chitosan and modified with TPP	Cd^{2+}, Co^{2+}, Cu^{2+}, Pb^{2+}	qmax = 91.75, 93.00, 87.25 and 99.96 mg g^{-1}, respectively	Magnetic recovery and surface functionalizatio n	[26]
Chitosan-based magnetic nanocomposite	V-CMN	Chitosan/Fe_3O_4 modified with vanillin	Cd^{2+}, Co^{2+}, Cu^{2+}, Pb^{2+}	qmax = 92.5, 94.0, 88.75 and 99.89 mg g^{-1}, respectively	Magnetic separation and chemical modification	[26]

Nanoadsorbent category	Materials	Functional feature	Target pollutant(s)	Applications	Main advantage	Reference
Hybrid ion-exchange nanoadsorbent	HFO-embedded ion-exchange resin	Hydrous ferric oxide nanoparticles embedded within ion-exchange resin	Cr(VI), Cd^{2+}, Pb^{2+}	Applied to acidic mine-drainage-related metal removal	Combines nanoparticle adsorption with ion exchange	[27]

3. Synthesis and Characterization

3.1 Conventional and Green Synthesis

Conventional approaches for synthesizing nanoparticles include co-precipitation, sol-gel, hydrothermal, and chemical reduction approaches. They provide excellent control over the size, shape, and composition of nanoparticles [28]. The co-precipitation method is commonly used to synthesize magnetic iron oxide-based nanoadsorbents. Co-precipitation is achieved by the precipitation of metal ions under alkaline conditions [28]. The sol-gel process allows for a controlled synthesis of the metal-oxide networks via hydrolysis and condensation reactions. The sol-gel process can yield homogeneous and crystalline nanoparticles upon heating [29]. In the hydrothermal synthesis approach, high temperature and pressure are employed to enhance the crystallinity and morphology of nanoparticles. This approach is ideal for synthesizing metal oxides with high structural integrity [30]. However, conventional synthesis approaches can be limited by toxic reagents and high energy requirements. This has stimulated research into environmentally friendly approaches to nanoparticle synthesis [31].

Green synthesis makes use of plant extracts, algae, microorganisms, or compounds derived from biomass as the reducing and stabilizing agents. This process will be able to minimize the use of dangerous chemicals while fabricating the nanoparticles [32]. Plant extracts consist of polyphenols, flavonoids, proteins, and various phytochemicals that can play a part in nanoparticle fabrication. In addition, they may act as capping agents on the surfaces of nanoparticles [33]. For instance, Prosopis farcta extract was used to fabricate Fe_3O_4 nanoparticles for methylene blue adsorption. The nanoparticles were fabricated in a plant-mediated process and exhibited good dye-removal capability [33]. Furthermore, green synthesis is applicable in the case of ZnO nanoparticles using the Nauclea latifolia fruit extract. The nanoparticles exhibited a crystalline size around 14.4 nm and significant methyl green removal capability [34]. Agricultural wastes can serve as another sustainable source of nanoparticle production. As an example, palm-petiole extract was employed in zero-valent iron nanoparticle fabrication for Cr(VI) removal [35]. Hence, green synthesis could be used to cut down chemical consumption by transforming natural biological materials into nanoadsorbent materials. But reproducibility and scalability still remain issues [36].

3.2 Physicochemical Characterization

The physicochemical characterization provides information on structure, morphology, surface chemistry, and stability of the synthesized nanoadsorbents. Several techniques are needed [37]. X-ray diffraction (XRD) shows the crystalline phases and provides information on the crystallite size. It is used to confirm the synthesis of nanoparticles [34]. Fourier-transform infrared spectroscopy (FTIR) helps to identify the surface functional groups. Any change in FTIR bands after adsorption might point to the participation of certain groups in the pollutant adsorption [38]. Scanning electron microscopy (SEM) gives information on the surface morphology and agglomeration. Transmission electron microscopy (TEM) gives more detailed information on the size and shape of particles [33]. Energy-dispersive X-ray spectroscopy (EDS) shows the chemical composition of the nanomaterials. It confirms the presence of certain elements in the synthesized nanocomposites [38]. Brunauer–Emmett–Teller (BET) gives the values of the specific surface area and pore characteristics. A greater accessible surface area might give additional adsorption sites for pollutants [34].

The determination of the zeta potential allows one to determine the electrical charge of the surfaces and helps elucidate the electrostatic forces between adsorbates and adsorbents [37]. Vibrating sample magnetometry (VSM) is necessary for magnetic nanoadsorbents. This technique determines the magnetic properties of nanoadsorbents and assesses magnetic separation after purification (3). The determination of optical properties and formation of nanoparticles can be performed using UV–Visible spectroscopy. This

method is also helpful for assessing the concentration dependence of some nanomaterials [29]. The thermal analysis gives information about the stability and decomposition of organic compounds in nanocomposites, which is needed when polymeric or biomass materials are introduced in nanoadsorbents [36]. Overall, the methods of XRD, FTIR, SEM/TEM, EDS, BET, zeta-potential, and magnetic properties give a complete description of the properties of nanoadsorbents and their relation to the material properties and adsorption efficiency [39].

4. Adsorption Mechanisms

4.1 Surface Complexation

Surface complexation happens through the reaction of pollutants with reactive sites on the surface of an adsorbent [40]. The surfaces of metal oxides can offer hydroxyl groups to interact with metal ions in solution [41]. Such interactions can result in either inner- or outer-sphere surface complexation [42]. Surface complexation is heavily influenced by the pH level because the process of protonation affects the sites on the surface [40]. The spectroscopic methods include XPS and X-ray adsorption spectroscopy [42].

4.2 Electrostatic Interaction

Attraction of oppositely charged pollutants and surfaces leads to electrostatic interaction [43]. It implies that positively charged ions can be attracted by the negatively charged adsorption surfaces [43]. Electrostatic interaction is especially relevant in cases of ionic pollutants since the charge of ionic pollutants is responsible for adsorption [44].

4.3 Ion Exchange

The ion exchange method comprises exchanging exchangeable ions in an adsorbent with pollutant ions in solution [27]. It ensures charge balance and transfers the desired ion into the adsorbent phase (68). This technique is significant in materials with exchangeable ions, both anions and cations, such as ion exchange resins and layered materials [27]. Ion exchange may take place at the same time as electrostatic interactions and surface complexation [46].

4.4 Chemisorption and Physisorption

Adsorption may take place by way of physical and chemical bonds formed between pollutants and adsorbent surfaces [47]. The process of physisorption usually takes place by means of weaker bonds like van der Waals interactions and hydrogen bonding [48]. In chemisorption, stronger bonds, which include chemical bonding, are involved [47]. Covalent bonding or ionic bonding can lead to chemisorption on functionalized nanomaterials [49]. Both mechanisms can occur simultaneously depending on surface chemistry and pollutant properties [50].

5. Heavy Metal Removal

5.1: Pb, Cd, Cr and Hg

Among the most concerning heavy metal pollutants in terms of toxicity and their bioaccumulation and environmental persistence include lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg) [51]. The potential applications of nanoparticle-based adsorbents in treating such metals are very high due to the large surface area and numerous active sites on the surface, which allow interaction with metal ions [25]. Thus, the graphene oxide-zirconium hybrid composite demonstrated maximum adsorption of Pb(II), Cd(II), and Hg(II) of 373, 320, and 281 mg g^{-1}, correspondingly [25]. Likewise, chemically and green-synthesized zinc oxide nanoparticles proved to be highly effective in the removal of different metals from wastewater, both synthetic and industrial. Modified graphene oxide with amino, hydrazino, and thiol groups showed affinity to Hg(II), Cr(VI), and Pb(II), with the maximum adsorption of 370.0, 136.2, and 109.6 mg g^{-1}, correspondingly [19].

5.2 As, Ni, Cu and Zn

Another group of pollutants, such as arsenic (As), nickel (Ni), copper (Cu), and zinc (Zn), which are commonly found in industrial and polluted water, also needs to be efficiently removed due to their toxicity and possible impacts on the environment [52]. Magnetite-embedded graphene oxide obtained from spent batteries removed 98% of As(III) ions at pH 7 during 20 min, with a maximum adsorption capacity of 50.2 mg g^{-1} [53]. Mesoporous magnetic carbon composites containing La-Fe and Zr-Fe phases had the maximum adsorption

capacity for As(III) of 116.25 and 109.89 mg g^{-1} and for As(V) – 166.67 and 144.93 mg g^{-1}, respectively [54]. As for Ni and Zn ions, surface-modified natural zeolite showed highly improved uptake capacity, reaching removal of 86.67% and 88.49%, respectively, while Cu ions were removed with an efficiency of 99.96% in multielement solutions [55]. Moreover, sodium trititanate nanorods were effectively utilized for the removal of Cr(VI), Cu(II), and Ni(II) ions from real electroplating wastewater [56].

6. Organic Pollutant Removal

6.1 Dyes and Pharmaceuticals

Synthetic dyes are persistent contaminants of the wastewater streams due to their stability and resistance to conventional treatments. Nanocomposites based on magnetism allow for effective adsorption and easy separation following the treatment process [57]. In addition, carbon ferrite-based nanomaterials could be used for pharmaceutical residue removal due to surface interaction and magnetic recovery properties [58].

A composite of iminodiacetic acid-modified graphene oxide and Fe_3O_4 was synthesized by Abdolmaleki et al. (2024) for the removal of MB and MO. The highest adsorption capacities were found to be 437.10 mg g^{-1} and 165.65 mg g^{-1} for MB and MO, respectively. Electrostatic interaction, hydrogen bond formation, and π and π-π interactions played important roles in MB/MO adsorption. The MB adsorption capacity was maintained during five cycles. Moreover, Iuliano et al. (2024) have studied FLG/Fe_3O_4/Ag@PAA nanocomposite for MB removal from water solutions.

Pharmaceutical sorption has also benefited from hybrid magnetic nanoparticles. Mg,Fe-LDH·Fe_3O_4 nanocomposites attained the maximum sorption capacity of 153.2 and 143.2 mg g^{-1} at pH 7.5 for diclofenac. The FTIR and XRD findings showed that electrostatic and complex formation were the mechanisms of sorption [58]. In addition, a PANI/GO/MOF-Fe_3O_4 nanocomposite was designed to adsorb methyl orange and naproxen sodium simultaneously [59].

6.2 Pesticides and Emerging Pollutants

The pesticides may continue to exist in aquatic ecosystems due to their extensive use and stability [60]. Composites using graphene oxide offer functional surfaces for pesticide adsorption and can be fabricated from biomass in agriculture. Kuppusamy et al. (2024) have developed the sugarcane-bagasse-cellulose/graphene oxide nanocomposite for atrazine removal and found the highest adsorption capacity to be 143.29 mg g^{-1}. Clay composites modified with LDH have also been used in the removal of atrazine and 4-chloro-2-methylphenoxyacetic acid (MCP). The LDH@Mt composite has demonstrated adsorption capacities of 8.19 mg g^{-1} and 90.9 mg g^{-1} for atrazine and MCP, respectively [60].

Organic emerging contaminants include drugs, antibiotics, and other biologically active chemicals commonly found in water systems. These need the use of adsorbents that have appropriate surface chemistry and a sufficient number of interaction sites (Table 2). It was found that Mg, Fe-LDH·Fe_3O_4 nanocomposites had successful adsorption capacity of diclofenac to the extent of 153.2 and 143.2 mg g^{-1} at a pH of 7.5. The stability of these nanoparticles remained even after three regeneration cycles [58].

Table 2. Recent nanoparticles used as adsorbents for organic pollutants.

Pollutant	Nanoadsorbent	Removal performance	Reference
Methylene blue	IDA-GO@Fe_3O_4	437.10 mg g^{-1}	[57]
Methylene blue	FLG/Fe_3O_4/Ag@PAA	141.60 mg g^{-1}; 98%	[61]
Diclofenac	Mg, Fe-LDH·Fe_3O_4	153.2 mg g^{-1}	[58]
Atrazine	Sugarcane-bagasse cellulose/GO	143.29 mg g^{-1}	[62]
Atrazine + MCP	LDH-modified clay	Composite-dependent	[60]
Methyl orange	PANI/GO/MOF-Fe_3O_4	239.78 mg g^{-1}	[59]

Pollutant	Nanoadsorbent	Removal performance	Reference
Naproxen sodium	PANI/GO/MOF-Fe_3O_4	40.64 mg g^{-1}	[59]

7. Multifunctional Nanocomposites

7.1 Multi-Pollutant Removal

The presence of more than one pollutant in real wastewater samples is common; thus, the development of multifunctional nanocomposites that incorporate various removal mechanisms is being pursued. Wang et al. (2024b) prepared Fe_3O_4/P(NIPAM-co-MAA)/Ag–TiO_2 that can remove a mixture of basic fuchsin and ciprofloxacin. It adsorbed the organic dye and photodegraded the antibiotic ciprofloxacin using visible light. According to Chandra et al. (2023), chitosan-based magnetic nano-sorbents were found to be capable of removing Cd, Co, Cu, and Pb ions from industrial wastewater. Hybrid materials also help in achieving selectivity in metal ion removal. For instance, GO-ZrATMP displayed maximum adsorption capacities for Pb^{2+}, Cd^{2+}, and Hg^{2+} as 373, 320, and 281 mg g^{-1}, respectively. This material was also examined in real wastewater [25].

HFO-containing ion exchange resins were developed for Cr(VI), Cd(II), and Pb(II) remediation and performed well both in simulated and natural acid mine drainage [27]

7.2 Applications to Real Wastewater Samples

Lab solutions yield valuable information about sorbents' performance, yet may not always be reflective of real wastewater characteristics. Thus, Chandra et al. (2023) tested magnetic chitosan nano-sorbents in real wastewater samples collected from textile-dyeing and footwear factories. The sorbents exhibited good contaminant removal capacity despite being subjected to untreated wastewater. GO-ZrATMP was tested on real wastewater samples as well and proved to have good prospects for heavy metal elimination [25].

In real wastewater samples, there may be other ions and organic substances that hinder the adsorption process. Therefore, future research efforts should concentrate more on the complex composition of wastewater instead of synthetic solutions. Multifunctional Fe_3O_4/P(NIPAM-co-MAA)/Ag-TiO_2 nanocomposites illustrate the approach to combine adsorption and photocatalysis processes in mixed contamination conditions [63]. Furthermore, magnetic separation could make nanocomposite collection much easier [58].

8. Regeneration and Environmental Safety

8.1 Regeneration and Reusability

Regeneration is vital for minimizing the amount of adsorbent needed and minimizing costs. Chitosan nano-adsorbents with magnetic properties preserved more than 75% of their adsorption efficiency after four cycles of recycling for different heavy metals [26]. Similarly, green-synthesized NiO nanoparticles preserved Pb^{2+} removal efficiency up to five times, which is another piece of evidence of reusability [64].

The other advantage of using magnetic nanocomposites is that they can easily be separated with the help of an external magnetic field. Mg, Fe-LDH·Fe_3O_4 preserved its structure and magnetic efficiency after three cycles of regeneration [58]. Likewise, HFO-based hybrid ion-exchange resins can also be regenerated with the help of NaCl to recover Cd and Pb [65].

8.2 Leaching and Toxicity

Environmental safety of the nanoparticles should be assessed before their wide use. Metal ions can be released from nanocomposites during treatment and regeneration processes. Therefore, HFO hybrid resin systems were examined for possible metal release and regeneration characteristics during wastewater treatment [16]. Additionally, the potential metal release of magnetic LDH/Fe3O4 during pharmaceutical adsorption was studied [58].

9. Challenges and Future Prospects

9.1 Scale-up and Sustainability

Despite excellent laboratory results, scale-up of nanoadsorbents faces difficulties. Expensive synthesis, aggregation, regeneration problems, and separation may prevent practical application. Current literature points to the fact that new adsorbents have to be studied for their economic and ecological viability and not only for their adsorption ability (54). The use of green synthesis involving biomass extracts and waste materials can lower the use of chemicals and make this technology sustainable. One example of this synthesis method is green NiO synthesis with the use of Lactuca sativa [23].

Tests in real wastewater should become the norm of nanoadsorbent investigation. A complex matrix can affect the adsorption process due to competitive adsorption or changes in pH or ionic strength. Application of chitosan-based magnetic nanoadsorbents has already been demonstrated in the case of real wastewater of textile and footwear industries [26]. Real wastewater tests were also successfully performed in the case of GO-ZrATMP [25].

9.2 AI-Assisted Design and Future Directions

AI and machine learning algorithms have the potential to optimize the design of new adsorbents. These techniques help connect material characteristics and operation parameters with adsorption performance. New studies indicate that AI-assisted material design is one of the trends in adsorption technologies for wastewater purification [64].

Nanoadsorbents of the future must have high capacity, selectivity, magnetic separation, and regeneration abilities. Nanomaterials might also be designed to perform adsorption and photocatalytic degradation processes at once. The Fe_3O_4/P(NIPAM-co-MAA)/Ag-TiO_2 composite shows this approach through its dye adsorption and antibiotic photodegradation capabilities [63].

10. Conclusion

Adsorbents based on nanoparticles have proved themselves to be efficient materials for the treatment of various heavy metals and organic pollutants present in polluted water. High surface area, adjustable surface chemistry, and numerous active sites can be helpful for the better adsorption of pollutants in comparison with some conventional adsorbents. Modern research proves the viability of metal oxides, carbon-based nanomaterials, magnetic nanoparticles, and multifunctional nanocomposites for the purification of Pb, Cd, Cr, Hg, As, Ni, Cu, Zn, dyes, drugs, and pesticides.

The adsorption efficiency is greatly influenced by the surface characteristics and features of pollutants. Such mechanisms as surface complexation, electrostatic interactions, ion exchange, chemisorption, and physical adsorption can function independently or jointly. The functionalization increases the number of active sites and their selectivity, whereas the presence of magnetic components helps in the recovery of the adsorbents.

Green synthesis offers a way forward to more sustainable manufacture of nanoadsorbents. Plant extracts, biomass, and other renewable sources will ensure lower usage of toxic materials as well as help achieve valorization of waste. Nonetheless, reproducibility, stability of particles, aggregation, and scale-up still pose certain challenges. Hence, future studies should focus on the evaluation of not only adsorption capacities but also regeneration efficiencies, material stability, nanoparticle leaching, toxicity, and lifecycle impacts.

Validation on real wastewater is especially crucial because of the presence of competing ions, organic substances, variable pH values, and pollutant mixtures that may affect adsorption efficiency. That is why researchers should pay much attention to continuous systems, industrial effluents, repeated regeneration, and long-term operation. Economic evaluation is equally crucial for determining the practical application of advanced nanoadsorbents

Nanoadsorbents for future research should be designed as multifunctional, recyclable, and environmentally friendly materials that can purify water from multiple impurities. Adsorption combined with photocatalysis, magnetization, eco-friendly methods of material fabrication, and computer-aided materials design may increase the efficiency of the process. Artificial intelligence and machine learning technologies can assist in

predicting the performance of the adsorption process and optimizing the material properties and operational parameters. Thus, nanoadsorbents seem to be a promising technology for wastewater purification. However, further successful implementation will require balancing several aspects.

Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

Khadija-Tul-Kubra, Conceptualization, literature search, data collection and analysis, manuscript drafting, and visualization. Fiza Saleem, Literature analysis, manuscript review, and writing review and editing. Shafaqat Ali and Rashid Iqbal, supervision, critical evaluation, and writing review and editing.

Data Availability

No new data were generated or analyzed in this review article. All information discussed in this article was obtained from previously published literature.

AI-assisted writing

AI-assisted tools were used during the preparation of this manuscript for limited language editing and improvement of clarity. The authors reviewed, verified, and approved all content and remain responsible for the accuracy and integrity of the manuscript.

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