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IRON OXIDE-BASED NANOMATERIALS FOR EFFICIENT REMOVAL OF HEAVY METALS FROM AQUEOUS SYSTEMS: MECHANISMS AND ENVIRONMENTAL APPLICATIONS

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Abstract

At the present time, the population has been increasing day by day, and the requirement for usable water is also crucial to support the exponentially growing population. The water needs to be cleaned and purified using various water purification techniques and technologies to meet the above demand. The polluted water is responsible for severe health concerns like cancer, neurological disorders, and kidney damage, etc., due to the presence of lead and cadmium in water through industrial waste. There are several conventional techniques and methods that are in regular use for water treatment, but are not sufficient for proper cleaning. The lags of conventional methods can be overcome by using nanotechnology. There are various nanomaterials available, but in this study, we discuss iron oxide-based nanomaterials, as they are widely recognised as effective for treating heavy metal-contaminated water. In this review, we have discussed synthesis methods, properties, and mechanisms of action, along with their environmental applications. This study also emphasises the current advantages and disadvantages of these materials and the importance of developing eco-friendly, scalable, and recyclable technologies for future applications.

KEYWORDS: Iron oxide nanomaterials, heavy metal removal, adsorption mechanisms,
Waste water treatment, environmental remediation

1. INTRODUCTION

Water contamination caused by heavy metal pollution in the water systems has become one of the most critical concerns in the environment, as it is persistent, toxic, and has become common in various water systems globally. The fast urbanization, industrialization, and population increment has augmented the release of dangerous contaminants into water bodies, leading to deposits of toxicants in surface and subsurface water sources (Mbuyazi & Ajibade, 2024)(Olawade et al., 2024). The metals including lead, cadmium, mercury, chromium, and arsenic, which are often found in contaminated water, are dangerous because they are at high-risk levels even in low amounts (Qasem et al., 2021). The growing occurrence of these pollutants clearly shows the importance of effective remediation approaches that would guarantee safe water supplies and environmental sustainability.

Industrial effluents, mining, electroplating, farm drainage, and urban sewage are the key reasons of heavy metal pollution. The discharge of effluent that contains toxic metals by industrial plants (textile, chemical and metallurgical industries) into water bodies without proper treatment is often a common phenomenon (Rajendran et al., 2023)(Yadav et al., 2023). Mining and ore processing operations are some of the main causes of metal leaching into the surrounding ecosystems, with electroplating and battery production industries being the main contributors of chromium, lead, and cadmium pollution (Baby et al., 2022). The other cause is the farming activities, whereby the fertilizers and pesticides cause the release of heavy metals to the soil, which is later washed away by runoff to water systems. Further, municipal wastes and sewage are uncontrolled, thereby contributing to water pollution, particularly in urban regions (Soni et al., 2023). The long time persistence and non-biodegradability is one of the peculiarities of the heavy metals. Heavy metals cannot decompose into harmless compounds, in contrast to organic pollutants, but rather they are stored in organisms through bioaccumulation and biomagnification (Tchounwou et al., 2012). This will result in the long-term pollution of the water bodies and will cause greater risks of transmission through the food chains, which ultimately will have impacts on human health. Plant, animal, and microorganism accumulation of heavy metals leads to ecological imbalance and poses a threat to biodiversity (Rajput et al., 2024).

The toxicological implications of the heavy metals on human health and the ecological systems have a great impact. Contact with polluted water can lead to neurological disorders, damage to the kidneys, liver dysfunction, and cancer of various types(Jaishankar et al., 2014). As an example, the exposure to chromium is related to liver and gastrointestinal damage, whereas lead and cadmium are related to neurological impairment and dysfunction of the kidneys. In water bodies, heavy metals inhibit physiological and metabolic activities in organisms, causing slow growth, lower reproduction, and survival rates, and causing an imbalance in the ecology (Olawade et al., 2024). Figure 1 represents the process of heavy metal exclusion by iron oxide-based nanomaterials.

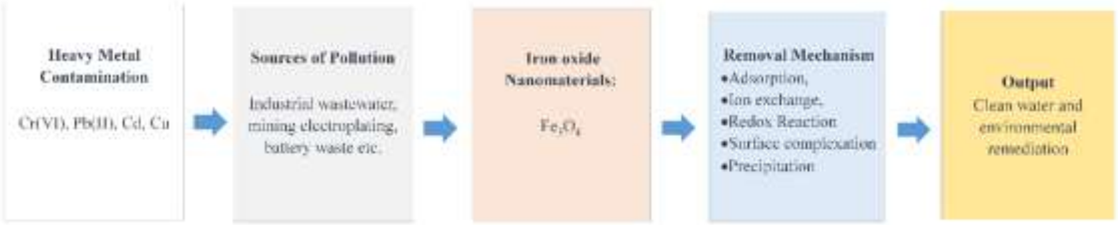

Fig 1. Schematic representation of heavy metal removal from wastewater using iron oxide-based nanomaterials and their environmental remediation mechanism

In a bid to remedy heavy metal pollution, several traditional treatment processes have been established, comprising ion exchange, coagulation-flocculation, adsorption, chemical precipitation, and membrane filtration using bulk solids. Despite these widely used methods, they possess significant shortfalls. During chemical precipitation, sludge in large quantities is usually formed that needs additional treatment and membrane filtration and ion exchange methods are linked with expensive maintenance and operational costs (Abdel Maksoud et al., 2020)(Olawade et al., 2024). Furthermore, the mechanisms might not be effective at low levels of the metal and are generally not selective, resulting in partial elimination of contaminants.

Nanotechnology is now proving a boon in the area of water remediation. Nanomaterials are characterized by high surface area, increased reactivity, and controllable surface chemistry, among others, which make them highly effective in the elimination of contaminants (Baby et al., 2022)(Tarekegn et al., 2021). Iron oxide nanoparticles have garnered significant interest due to their high efficiency, environmental friendly and low-cost. These materials are able to eliminate heavy metals using several different processes, including adsorption, complexation, and redox reactions (Hua et al., 2012).

Iron oxide nanoparticles have a number of benefits compared to traditional adsorbents. They can be separated easily through an external magnetic field, resulting in the easy recovery and reuse of the nanomaterials (Dave & Chopda, 2014). Also, they possess a high surface area and tunable surface functionality that increases the adsorption capacity and selectivity towards different heavy metal ions. These nanoparticles are not as toxic and can be produced through economical and environmentally sustainable technologies (Popescu et al., 2025).

The purpose of this review is to offer a detailed study of iron oxide nanomaterials used in the purification of water bodies of heavy metals by aqueous systems. The paper presents the synthesis strategies of iron oxide nanomaterials, their mechanism in heavy metal removal, and environmental uses, and further considers the challenges faced and the scope for future developments. Through recent advancements, the research demonstrates the effective nature of iron oxide nanomaterials as green technologies for reducing heavy metal pollution in water systems.

2. Iron Oxide Nanomaterials: Types, Properties, and Functionalization

2.1 An overview of Iron oxide nanomaterials

One of the most diverse nanomaterials are the one with iron oxides because of their polymorphic nature, varying features, and wide application in the environment and technology. The most prominent types are the magnetite (Fe_3O_4), hematite (α- Fe_2O_3), and maghemite (γ- Fe_2O_3), which possess different structural and physicochemical features (Ajinkya et al., 2020)(Campos et al., 2015). Their presence is related to crystal arrangement and oxidation state shifts of iron, which directly impact reactivity, stability, and magnetism. Due to their strong magnetic properties, magnetite and maghemite are widely used in environmental applications, while hematite is valued for its thermodynamic stability at room temperature (Ganapathe et al., 2020).

2.2 Crystal structure and phase characteristics

The fundamental process of iron oxides depends on their crystalline structure. With the vacancy of cation, maghemite has an identical spinel arrangement and is only mutually occupied by Fe^{3+}, whereas magnetite has an inverse spinel structure with Fe^{2+} and Fe^{3+} ions on tetrahedral and octahedral positions, respectively (Ajinkya et al., 2020). Hematite has a rhombohedral crystal structure in which Fe^{3+} ions occupy octahedral sites, providing good chemical stability. Such structural features affect its adsorption capacity as well as its electronic and magnetic properties, which are essential for effective pollutant removal (Ganapathe et al., 2020).

2.3 Reactivity and surface area

One of the main features of iron oxide nanoparticles is the great surface-to-volume ratio that gives the high reactivity and adsorption capacity to the nanoparticles. On the nanoscale, a significant portion of atoms is found on the surface, which has numerous active sites to interact with contaminants (Campos et al., 2015)(Sridevi et al., 2023). It is a substance that enables the easy binding of heavy metal ions as a result of surface complexation as well as via electrostatic interaction. Also, nanoscale components possess quantum size effects, which result in the change of optical, magnetic, and electronic characteristics in nanoproducts in comparison with bulk products (Campos et al., 2015).

2.4 Superparamagnetism and magnetic properties

Another characteristic of iron oxide nanomaterials is their magnetic properties, especially superparamagnetism. Nanoparticles displaying superparamagnetic properties (high magnetization in an external magnetic field and low residual magnetism when the field is removed) are shown when the particle size is less than a certain critical size, usually around 20 nm and below (Ganapathe et al., 2020)(Aida et al., 2023). The property is particularly favourable in application to water treatment because nanoparticles can be readily separated and reclaimed by applying external magnetic fields. This property is very helpful as it adds to the enhancement of reusability and operational efficiency.

2.5 Factors influencing the adsorption performance

The particle size, morphology, and surface charge of iron oxide nanoparticles have a strong impact on the adsorption performance. Smaller nanoparticles, as they have more surface area and active sites, have achieved increased adsorption efficiencies. The presence of adsorption sites and diffusion paths are impacted by morphological features such as spheres, cuboids, or aggregates (Sridevi et al., 2023)(Chakraborty et al., 2024). The removal effectiveness of metal ions by nanoparticles is heavily influenced by electrostatic attraction between the charged surface of the nanoparticles and metal ions in the solution. The surface charge characteristics, commonly characterised by zeta potential, are essential in affecting adsorption efficiency across various pH levels (Hua et al., 2012).

2.6 Stability issues in aqueous systems

Iron oxide nanomaterials also have several challenges associated with stability issues in the aqueous systems. Lower adsorption performance is caused by magnetic and van der Waals aggregation, and it minimises the surface area (Bustamante-Torres et al., 2022). Also, magnetic and structural features are changed during the oxidation and transition phase, and it impacts the performance as well (Ajinkya et al., 2020). So, this states that there should be strategic ways of surface modification to improve the stability and performance.

2.7 Surface functionalization strategies

Functionalization of the surface is essential for enhancing the efficiency of iron oxide-based nanomaterials. Coating of nanoparticles with carbon-based materials, silica polymers, or biomolecules helps prevent aggregation and enhances the dispersibility of aqueous media (Sridevi et al., 2023)(Pourmadadi et al., 2022). These coatings add a functional group to the nanoparticles, which results in high affinities and selectivity of heavy metal ions and the adsorption capacity (Schneider et al., 2022). Moreover, through biomolecules and surface modification, ligands can be attached, which leads to specific interactions and higher environmental compatibility.

The performance of iron oxide nanoparticles has also been improved by the development of hybrid and composite nanomaterials. The addition of iron oxides to polymers or other substances leads to more stable nanocomposites, high adsorption properties, and reusability (G. Zhao et al., 2018). Synergistic effects are characteristic of these hybrid systems, in which the nature of various elements can result in the best performance of the entire system than that of specific materials.

Thus, due to the structural, magnetic, and surface peculiarities of iron oxide nanomaterials and innovative methodologies of functionalization, they can be used successfully in environmental remediation. There are also ongoing developments in surface engineering and composite development, which will further increase their usability in the treatment of water in a sustainable manner (Laurent et al., 2008)(Qu et al., 2013).

3. Synthesis approaches and their influence on material performance

3.1 Overview of synthesis of iron oxide-based nanomaterials (conventional and chemical)

The synthesis of iron oxide nanomaterials is a key determinant of their structural and functional characteristics, which directly affect their functionality in environmental and technological usage. Properties such as morphology, particle size, crystallinity, surface charge, porosity and magnetic behaviour are highly dependable on the synthesis route and reaction conditions used during nanoparticle fabrication. Because of this, the selection of a suitable synthesis method is essential for designing efficient iron oxide nanomaterials for applications such as heavy metal removal, catalysis, drug delivery, catalysis, sensing, and wastewater treatment (Laurent et al., 2008). Numerous synthesis methods have been developed for the preparation of iron oxide nanomaterials, which include wet chemical synthesis strategies, physical techniques, and emerging sustainable methods. More commonly used methods are conventional chemical synthesis approaches such as co-precipitation, sol-gel, hydrothermal (uses water as the solvent) and solvothermal (uses non-aqueous organic solvents like alcohols and organic liquids) because of their nature of using various techniques and being able to regulate the properties of each particle (Aruchamy et al., 2023)(Szczyglewska et al., 2023). Those techniques are based on the controlled chemical processes of the precursors, solvents, and stabilising agents to have specific morphological and surface characteristics of nanomaterials. In particular, chemical reduction approaches are preferred due to their simplicity, affordability, and the possibility of obtaining nanoparticles with a specific size and distribution by carefully modelling the reaction parameters (Szczyglewska et al., 2023). Researchers can adjust these parameters to customise the adsorption characteristics, magnetic features, and surface chemistry of the nanoparticles for particular environmental uses by coupling iron oxide nanoparticles with materials like polymers, silica, activated carbon, biochar and graphene oxide. These types of combinations make the nanoparticles more reusable, stable, and effective in removing the heavy metals, also reducing the clumping problems. Overall, different types of synthesis methods enable the production of iron oxide nanomaterials with desired properties, and ongoing advancements are expected to augment their safety, performance, and large-scale applications in wastewater treatment and surrounding environments (G. Zhao et al., 2018). Figure 2 provides a graphic depiction of synthesis approaches.

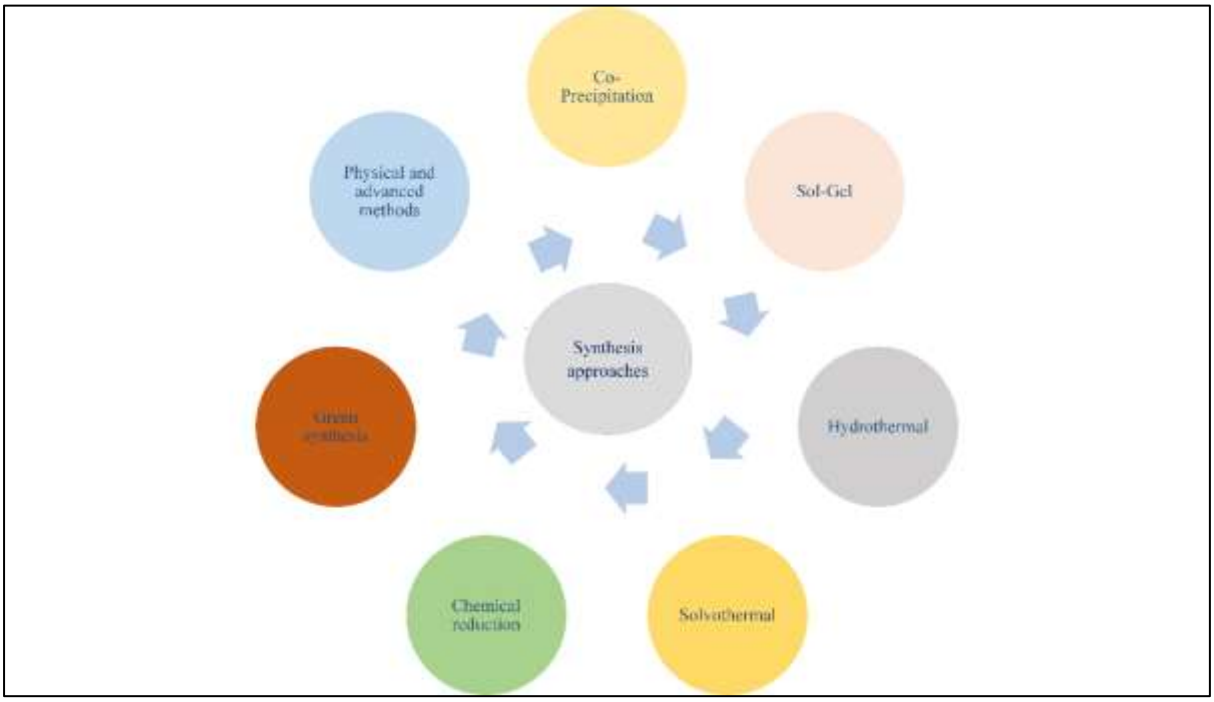

Fig 2. Circular schematic representation of synthesis approaches for iron oxide-based nanomaterials

3.2 Techniques and approaches for synthesis of iron oxide-based nanomaterials

The solvothermal and hydrothermal processes are used for iron oxide-based nanomaterials because they allow operation under high-temperature and high-pressure conditions, which are favourable for producing highly crystalline materials with better structural stability, thereby enhancing crystal growth and improving the adsorption and magnetic characteristics of iron oxide nanostructures (Aruchamy et al., 2023). Water is commonly used in hydrothermal strategy, while organic solvents such as ethylene glycol or ethanol are used in solvothermal strategy. These techniques help produce various iron oxide nanostructures such as nanorods, nanospheres, nanotubes, and nanoflowers, which are highly effective for heavy metal removal and catalytic applications. Studies have shown that hydrothermally synthesised Fe_3O_4 nanoparticles exhibit enhanced adsorption performance toward toxic metal ions because of their improved crystallinity, larger surface area, and greater number of active adsorption sites. The methods, however, may require a significant amount of energy and processing time, which may hamper upscaling. On the same note, in materials science, it is common to rely on classic synthesis methods that rely on trial and error as experimentation, and systematic optimisation seems to be a crucial way to enhance efficiency and reproducibility (Chen et al., 2025). Through the creation of large databanks and data-centric methods, improved insight and control in over synthesis pathways, researchers can better control the structural and functional phases, making it possible to improve material design (Z. Wang et al., 2022). Pandey et al. have synthesized iron oxide nanoparticles on nickel foam via a hydrothermal approach at 120ºC (Pandey et al., 2025).

Alternative methods of creating nanomaterials that are more uniform and perform better are through physical and advanced methods of synthesis. As an example, plasma-assisted synthesis provides one-step, quicker fabrication of iron oxide nanocomposites with enhanced electrochemical characteristics and scalability (Beletskii et al., 2024). High-pressure homogenization is another novel technique that allows large-scale and continuous production with more efficiency compared to the traditional techniques, which are fraught with disadvantages, including low yield and bad reproducibility (X. Liu et al., 2023). Mechanochemical synthesis, another form of synthesis employing mechanical energy to drive chemical reactions, has now become energy-saving and solvent-free, has the ability to control the size and the morphology of the particles, and is also less harmful to the environment (Muaz et al., 2025). The ability of the selective extraction methods to create nanostructures by targeting certain components of a precursor material can also further extend synthesis possibilities (Naguib & Gogotsi, 2015).

Over recent years, sustainable and green synthesis methods have been an interconnected topic that has been gaining more attention for iron oxide-based nanomaterials development. These methods focus on minimising environmental impact by using eco-friendly solvents, biological reducing agents, renewable raw materials, and energy-efficient synthesis conditions. For the green synthesis of iron oxide nanoparticles, microorganisms, plant extracts, natural polymers, and agricultural residues are being used because they diminish the use of harmful chemicals and improve the surroundings. Furthermore, waste valorization approaches, where industrial or agricultural waste products are converted into useful nanomaterials, support circular economy principles and sustainable material development (Vakros et al., 2023)(Bekkeri et al., 2023). Kaleem et al. have produced iron oxide nanoparticles using cyanobacteria for the removal of cadmium and lead metals (Kaleem et al., 2024). Iron oxide nanoparticles produced through green synthesis have demonstrated effective adsorption capabilities for heavy metals like chromium, arsenic, lead, and cadmium, all while exhibiting reduced toxicity and improved biocompatibility.

The concentration of temperature, precursors, time of reaction, and after-treatment conditions can have substantial impacts on the performance and characteristics of materials (Aruchamy et al., 2023). Through the controlled synthesis of nanomaterials; the surface area, porosity, and ion transport properties can be increased, which are vital for applications like catalysis and adsorption. Moreover, the nature of the synthesis strategy determines the cross-linking density of materials and the internal structure. An impact on functional behaviour and performance of materials can be enhanced with precise synthesis approach (Mouhoubi et al., 2025).

Although great progress has been made in the iron oxide-based nanomaterials synthesis, there is still a problem of reproducibility and scalability. Some traditional approaches have the disadvantage that they can be expensive, ineffective, and are difficult to process on a large scale (X. Liu et al., 2023). Also, the time lag between synthesis and useful utilisation is often slow, and the materials initially created to do a particular job might subsequently be used in completely different areas (Taylor et al., 2023). The target is required to guarantee the stability of performance; therefore, efficient methods to synthesise materials would be important to achieve this.

In general, the synthesis technique is a critical factor when it comes to defining the effectiveness and versatility of iron oxide-based nanomaterials. To achieve better material properties, large-scale synthesis strategies are necessary to enhance the efficiency and to support their applications in environmental clean-up and other important sectors.

4. Mechanism of heavy metal removal by iron oxide nanomaterials

4.1 Adsorption and surface interactions

A complex of physicochemical and biological processes governs the removal of heavy metals from aqueous systems using iron oxide-based nanomaterials, and adsorption is widely accepted as the main mechanism of their removal due to its effectiveness and ability to operate under diverse conditions. Adsorption is the process that involves the adherence of metal ions to the adsorbent surface due to physical and chemical interactions between the surface and solution chemistry, and operative conditions (Qasem et al., 2021)(Vo et al., 2020). A primary mechanism of adsorption is electrostatic attraction between dissolved metal ions and the charged surface of iron oxide nanoparticles. Under favourable pH conditions, the nanoparticle surface often becomes negatively charged, stimulating the attraction of positively charged heavy metal ions such as Pb^{2+}, Cd^{2+}, Cu^{2+}, and Cr^{3+} (Vo et al., 2020). This interaction is extremely pH-sensitive because it affects both how this type of interaction can cause metal ions to precipitate and the surface charge of the adsorbent. Figure 3 illustrates several methods for removing heavy metals.

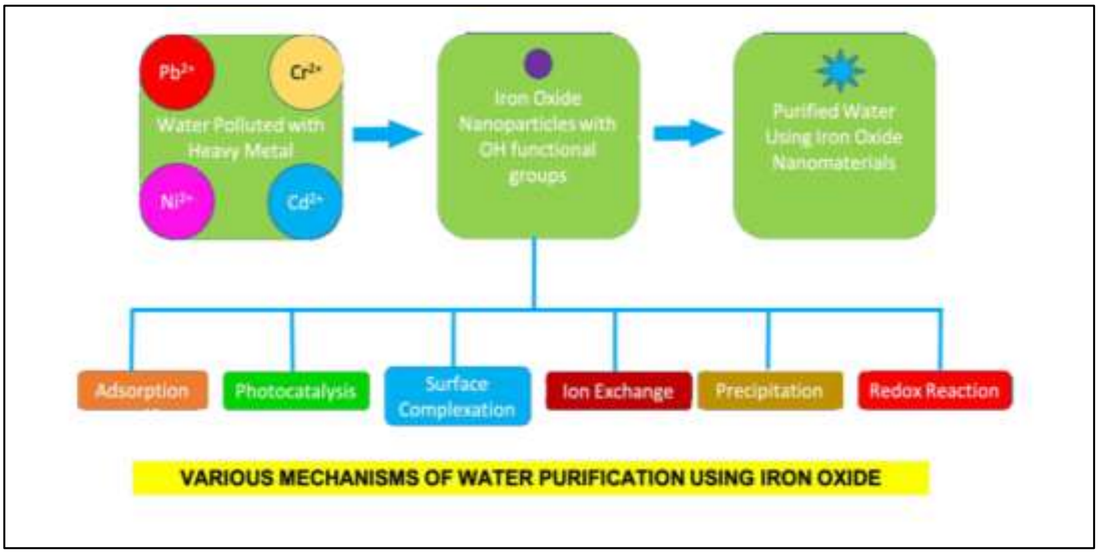

Fig 3. Different mechanisms of heavy metal elimination using iron oxide nanoparticles

In addition to the electrostatic interactions, surface complexation is a very essential factor in the binding of metals on iron oxide nanoparticles. This mechanism is based on the coordinating bonds between metal ions and functional groups of hydroxyl, carboxyl, phosphates, and amine groups on the adsorbent surfaces (Kurniawan et al., 2023). In biomaterials and composite systems, the affinity of these functional groups determines the selectivity and strength of adsorption. Table 1 summarises important historical and recent studies related to the mechanisms of heavy metal elimination using iron oxide-based nanomaterials.
Recent studies have shown that Fe_3O_4 nanoparticles significantly achieved better adsorption of Pb^{2+} and As^{5+} ions due to stronger surface complexation interactions (Gupta et al., 2021). Similarly, reports have stated that magnetic iron oxide nanocomposites exhibit strong adsorption performance for Cd^{2+} and Cr^{6+} removal under neutral pH conditions, supported by faster kinetics and a larger quantity of active adsorption sites (Bharti et al., 2022).

4.2 Ion exchange and biosorption processes

Likewise, ion exchange is a fundamental process, notably when it comes to iron oxide-based adsorbents and particularly in biochar-supported materials, polymer-coated or biologically modified nanomaterials. During this process, metal ions in the solution exchange with the ions on the adsorbent surface, namely H^+ or Na^+ (J. J. Zhao et al., 2019). The effectiveness of ion exchange is influenced by variables like ion concentration, ionic size, charge, and the selectivity of the adsorbent surface for precise metal ions. Biochar-supported Fe_3O_4 nanocomposites showed superior ion exchange for Cu^{2+} and Ni^{2+} ions because oxygen containing surface groups improved the accessibility of active sites. The biosorption efficiency of biologically modified iron oxide nanoparticles was ascribed to the combined impact of microbial-assisted metal uptake and stronger surface complexation mechanisms (Sharma et al., 2023). The elimination of heavy metals by iron oxide hybrid biosorbents primarily occurs via biosorption mechanisms, including ion exchange, adsorption, and complexation. The presence of biomass-derived functional groups further increases their ability to selectively adsorb toxic metals from wastewater (Ali Redha, 2020).

4.3 Redox, photocatalytic and precipitation mechanisms

Redox reactions are important in iron oxide-based nanomaterials because iron can transfer electrons and convert toxic metal ions into safer and more stable forms. One example is the reduction in toxicity of Cr (VI) to Cr (III), which aids in precipitation or adsorption (Z. Liu et al., 2022). Redox changes can lead to paired adsorption and sorption-reduction couples, boosting total removal outcomes. Photocatalytic systems such as those containing ZnO particles or Tio_2 exhibit both. Irradiation can decrease or oxidise metal ions, resulting in the formation of metal oxides (Le et al., 2019). Iron oxide nanocomposites with layered or nanosheets show rapid adsorption rates and solid binding interactions, leading to Langmuir isotherms, exhibiting monolayer adsorption. After 2015, major progress was made in the development of photocatalytic hybrid nanocomposites such as Fe_3O_4/FeOOH, PDA/Fe_3O_4, etc. which generated reactive oxygen species under visible light and greatly improved heavy metal removal along with degradation of toxic pollutants (Leonel et al., 2021).

By forming insoluble species, additional processes of precipitation and co-precipitation also helps in the removal of heavy metals. These reactions, whether alone or with adsorption, can produce stable compounds such as metal hydroxides or carbonates that precipitate onto or near the surface of iron oxide nanomaterials (Ali Redha, 2020)(Kurniawan et al., 2023). In some systems, metal ions are immobilised by micro-precipitation on the adsorbent surface. Earlier research showed that iron oxide-coated nanoscale zero-valent iron successfully transformed Cr(VI) into Cr(III), emphasizing the significance of redox-assisted remediation technologies in wastewater treatment (Niu et al., 2005).

4.4 Biological mechanisms and combined removal process

Biological and ecological methods, notably iron oxide nanoparticles, support phytoremediation and microbial remediation, use biochemical mechanisms to sequester or convert metals, bioaccumulate, biomineralize, and undergo enzymatic transformation (Sharma et al., 2023)(Alotaibi et al., 2021). Researchers use models like Langmuir and the Freundlich isotherms to better understand adsorption behaviour. Kinetic analyses frequently rely on pseudo-first-order and pseudo-second-order models, where the second-order model often reflects chemisorption effects (Raji et al., 2023; Vo et al., 2020; Zhang et al., 2020). Recent research showed that the synergistic use of biological treatment systems and magnetic iron oxide nanoadsorbents significantly strengthened remediation effectiveness, regenerative ability, and sustained operational performance in wastewater treatment applications (Tai et al., 2023).

Table 1. Historical and recent studies on mechanisms of heavy metal removal using iron oxide-based nanomaterials

Year	Iron oxide nanomaterial	Size/Shape	Mechanism	Merits	Demerits	References
2005	Iron oxide-coated nanoscale zero-valent iron	Nanospheres (~20–80 nm)	Redox-assisted reduction of Cr(VI) to Cr(III)	High reduction efficiency and rapid remediation	Agglomeration and inoxidation stability	(Niu et al., 2005)
2008-2012	Fe_3O_4 Nanoparticles	Spherical nanoparticles (~10–50 nm)	Adsorption through electrostatic attraction and surface complexation	High surface area and magnetic separation	Difficult recovery after repeated use	(Laurent et al., 2008)
2010-2015	Silica-, graphene oxide-, activated carbon-coated Fe_3O_4	Core-shell and layered nanostructures	Enhanced adsorption and recyclability	Better stability and reusability	Complex synthesis and higher cost	(Gupta et al., 2021)
2015-2018	Biochar-supported Fe_3O_4 nanocomposites	Porous and irregular nanostructures	Ion exchange and biosorption mechanisms	Improved active sites and eco-friendly nature	Reduced adsorption under competing ions	(J. J. Zhao et al., 2019)
2018–2020	Fe_3O_4/TiO_2 photocatalytic nanocomposites	Nanorods and nanospheres	Photocatalytic degradation and redox reactions	Visible-light activity and pollutant degradation	Energy-intensive synthesis	(Le et al., 2019)
2020-2021	Magnetic iron oxide hybrid nanocomposites	Core-shell and layered structures	Simultaneous adsorption and precipitation	Fast kinetics and high adsorption capacity	Surface fouling in wastewater systems	(Ali Redha, 2020)(Qasem et al., 2021)
2021-2022	Modified Fe_3O_4 nanoparticles	Nanoflowers and nanosheets	Surface complexation for Pb^{2+}, As^{5+}, Cd^{2+}, and Cr^{6+} removal	Enhanced selectivity and adsorption performance	Possible toxicity at high concentration	(Bharti et al., 2022)(Z. Liu et al., 2022)

2022-2023	Biological and magnetic iron oxide nanoadsorbents	Hybrid porous nanostructures	Combined adsorption, biosorption, and microbial remediation	Sustainable remediation and regeneration ability	Limited large-scale application	(Sharma et al., 2023)(Tai et al., 2023)
2023-Present	Green synthesized iron oxide nanomaterials	Nanoflowers, nanospheres, nanotubes	Eco-friendly adsorption and multifunctional remediation	Low toxicity and sustainable synthesis	Scale-up and reproducibility challenges	(Abd Elnabi et al., 2023)(Kurniawan et al., 2023)

5. Environmental and operational factors influencing heavy metal removal

Environmental and operational factors play a vital role in determining the success of heavy metal removal processes. Important parameters like pH, temperature, contact duration, metal ion concentration, and adsorbent dose directly affect adsorption performance and treatment efficiency (Ali Redha, 2020; Qasem et al., 2021). In actual water treatment systems, competing ions and natural organic matter can degrade performance by blocking active adsorption sites or modifying the adsorbent's surface properties. Furthermore, changes in ionic strength might alter electrostatic interactions between metal ions and iron oxide surfaces, thereby affecting overall adsorption. The difference in mechanics between the metals is also significant, and it is determined by the difference in the ionic radius, the valency, and the behaviour of the metals that interact with the adsorbents. To illustrate, electrostatic attraction can be used to selectively extract some metals, whereas other groups need certain functional groups or redox reactions to be effectively extracted (Le et al., 2019).

In most cases, heavy metal decontamination of aqueous systems is a complicated and multi-dimensional procedure that entails a set of adsorption, ionic exchange, complexation, redox conversion, and precipitation procedures. Combined with the development of material design and environmental engineering, the stream of these processes only supports the efficiency and applicability of heavy metal remediation technologies (Abd Elnabi et al., 2023).

6. Role of iron oxide-nanomaterials in the heavy metal removal

Removal of selected heavy metals using advanced adsorbents and nanomaterials has been extensively studied, and adsorption is acknowledged as the most effective and versatile method, as it is easy to use and has strong removal capabilities (J. Yang et al., 2019)(Zaimee et al., 2021). One of the most widely investigated domains is the extraction of lead (Pb^{2+}) due to its high toxicity and presence in industrial effluents. Functional adsorbents composed of nanomaterials show high affinity towards lead ions based on a strong electrostatic force and complexation of surface features with functional groups. Adsorption capacities have often been reported as high (up to several hundred mg/g under optimal conditions) in those systems where the adsorbent is porous and has many active sites to bind (J. Yang et al., 2019). Functional materials also improve the ability of lead to be absorbed through customized surface chemistry and access to more adsorption sites (Li et al., 2023). In an investigation carried out by Abdul-Gafaru et al., iron oxide nanomaterials have shown effective removal of 98.6% Pb (II) and 93% Cd (II) metals within 30 minutes (Abdul-Gafaru et al., 2025).

The removal of cadmium (Cd^{2+}) is even more difficult because of its high mobility and competition with other coexisting ions in the water system. Cadmium adsorption can be decreased in multicomponent situations as competitive interactions with other ions, including Pb^{2+}, Cu^{2+}, and Zn^{2+}, can use the same active sites (Bayuo et al., 2023). It demonstrates the significance of adsorbent selectivity that can be enhanced via surface modification and functionalization. When paired with ion exchange and surface complexation processes, it has been demonstrated that adsorption can be used to improve the efficiency of cadmium removal, especially with the help of composite or bio-based adsorbents (Zaimee et al., 2021). Sosun et al studied the removal of Ni^{2+} and Cd^{2+} using Fe_2O_3 and TOPO-coated Fe_2O_3 nanoparticles. The study followed the pseudo-second order kinetics (Sosun et al., 2022).

Removal of chromium is especially necessary because there are various oxidation states, with Cr (VI), i.e. very toxic and mobile, unlike Cr (III). Many successful strategies that prevent removal include adsorption and redox transformation, in which Cr(VI) is reduced to less toxic Cr(III) during or before adsorption (Selvi et al., 2019). Combined treatment systems that integrate chemical, physical and biological processes are very significant in enhancing the efficacy of chromium removal as a contaminant by allowing the process of detoxification and immobilization (Selvi et al., 2019). For instance, Pan and co-workers have synthesized CTAB and SA-coated iron oxide nanoparticles for Cr (VI) removal (Pan et al., 2019). Besides, Ismail et al studied Cr (VI) removal using Fe^{o}-Cu within 180 min with a maximum removal capacity of 295.7 mg/g with 3g/L dose (Ismail et al., 2025).

The higher ionic activity of arsenate [As (V)] and arsenite [As (III)] species renders it more difficult to remove arsenic, as they do not substantially interact but are chemically quite different. As(III) is more mobile and less adsorbed compared to As(V). As(V) has a higher level of affinity to adsorbent surfaces, in particular, to those with metal oxide functionalities (J. Yang et al., 2019). The effectiveness of the use of arsenic is determined by various aspects, such as the pH, as well as the oxidation state and the surface chemistry of the adsorbent, and needs specific treatment regime to attain optimal performance. Iron hydroxide nanopetalines has been synthesized by Wang et al, for removal of As (III) and As (V) with q_{max} of 91.74 mg/g and 217.76 mg/g at pH 4, respectively (Y. Wang et al., 2022).

The removal of mercury (Hg^{2+}) has been of particular interest because of its high toxicity and bioaccumulation properties. Sulphur-based functionalized materials are highly selective to mercury ions because they are highly binding and form complexes (Pohl, 2020). The effects of mercury pollution are linked to serious ecological and health issues, which further underline the importance of highly selective removal methods (Li et al., 2023). CS-Fe_2O_3@β-CD has been used by Kaur et al, for Hg^{2+} removal with q_{max} of 89.96 mg/g with a 0.08 g/L dose (Kaur et al., 2025).

This is illustrated by comparative studies, which have shown that the performance of adsorbents varies with the type of material, structure, and surface characteristics. Composite adsorbents and nanomaterials tend to be better materials in comparison with conventional materials because of increased surface area and tunable porosity, as well as their increased reactivity (J. Yang et al., 2019). In practical wastewater treatment systems, different metal ions are commonly found together, leading to competition for adsorption sites and reduced removal efficiency. These interactions can affect adsorption behaviour in both favourable and unfavourable ways (Bayuo et al., 2023). In wastewater systems, the presence of organic matter and other competing ions can interfere with adsorption processes and reduce contaminant removal performance. For this reason, factors such as temperature, pH, exposure time, and initial metal concentration must be carefully managed to ensure efficient treatment. (Zaimee et al., 2021). Although laboratory studies often show excellent heavy metal removal under controlled conditions, achieving the same efficiency in pilot-scale or industrial systems is challenging due to changing environmental conditions and engineering limitations.(Hama Aziz et al., 2023). Efficient remediation of heavy metals depends on selecting suitable treatment methodologies based on the features of the pollutants, adsorbent materials, and wastewater composition. Optimizing these parameters is important for long-term and effective treatment.

7. Environmental applications and practical implementation

The effectiveness of iron oxide nanomaterials in environmental clean-up have been attributed to their distinctive surface activity, magnetism and high reactivity, characteristics that have facilitated easy removal and conversion of pollutants. These materials are used in the treatment of wastewater as adsorbents and catalysts, which help in the treatment of pollutants and to separate pollutants. Their catalytic property i.e. in the Fenton-like reactions where oxide nanoclusters of iron oxide facilitate oxidative degradation of toxic substances at room temperature, enhancing better treatment performance and reducing power consumption (Z. Yang et al., 2025). These characteristics render them very acceptable to be integrated in the contemporary wastewater treatment facilities.

In industrial effluent treatment, such as mining, electroplating, and battery-related industries, iron oxide nanomaterials exhibit a high affinity to heavy metals and other dangerous pollutants. The quality of their performance is highly attributed to their tunable surface chemistry and high surface area, which aid in the enhancement of adsorption and catalytic interactions (Tanaka et al., 2019). Water purification becomes more efficient when iron oxide nanomaterials are combined with membranes and nanofiltration systems. These hybrid systems are adsorbent-filtration systems that improve the level of removal and ensure system power (Saif et al., 2016). Iron oxide nanoparticles have demonstrated remarkable efficacy in fixed-bed columns and continuous-flow systems, showcasing their suitability for large-scale and ongoing wastewater treatment processes. Their effective operation in changing environments demonstrates great potential for practical industrial applications. (Ogbezode et al., 2023).

The practical use of these materials has been shown through pilot-scale and field studies, confirming their effectiveness in actual treatment systems. Their successful application in waste detoxification and resource recovery underscores their potential for sustainable and large-scale environmental clean-up efforts (Z. Yang et al., 2025). However, there are still issues of laboratory scale achievement to field application, such as reproducibility, scale, and stability. Also, issues of environmental safety and possible toxicity require close consideration and control by the authorities (Saif et al., 2016). Despite these obstacles, iron oxide nanosystems have a bright prospect of decentralised systems of water purification, where their functionality, recyclability, and flexibility can assist sustainable and affordable water purification (Ogbezode et al., 2023)(Bakshi, 2024).

8. Advantages and limitations

The iron oxide nanomaterials are very promising for removing heavy metals due to their high efficiency, quick adsorption, and high affinity with diverse metal ions. These have a high surface area and a numeral active sites because of their nanoscale size, leading to better adsorption characteristics than traditional materials (Miras & Alhalili, 2023). Experimentally, it is demonstrated that with optimised conditions, such nanomaterials can have high removal efficacies of about metals Pb (II), Cd (II), Cr (VI), which are usually above 80%, and the adsorption behaviour is often pseudo-second-order, suggesting chemisorption processes (Khoso et al., 2021). They are further characterised by their magnetic properties, which allow them to separate and be recovered easily from treated water, facilitating greater reusability and other aspects of operability. Moreover, they are versatile across various heavy metals and environmental conditions, making them applicable to a variety of remediation applications (Mohamed et al., 2023).

Although they have these benefits, there are several constraints to their widespread use. Nanoparticles can be aggregated to a considerable degree, which may cause a substantial reduction in effective surface area and limit the efficiency of adsorption. Stability in different environmental requirements, such as oxidation and changes in the structure, may also impact performance (Miras & Alhalili, 2023). Also, even though the green synthesis methods improve the overall environmental friendliness, it is difficult to ensure steady particle properties (Mohamed et al., 2023). Eco-toxicological risks of nanoparticle release have to be evaluated carefully, as the effects in the long-term on the ecology are not comprehended. Moreover, issues concerning the cost, scalability, and regeneration need to be solved to implement these systems in industries (Khoso et al., 2021).

9. Future perspectives and research gaps

Research on iron oxide nanomaterials in the future ought to aim at closing the gulf that separates the success achieved in laboratories from large-scale application in water treatment systems. The urgency is to come up with efficient, cost-saving and scalable production processes that do not compromise on the quality of materials. It is imperative to progress towards environmentally friendly synthesis methods to lessen the environmental impact and increase sustainability. Nanocomposites designed with superior selectivity, stability, and multiple functions promise new avenues of improved performance.

Also, it should be aimed at enhancing the regeneration and recyclability to achieve long-term usage and efficiency. To know the possible effects of nanoparticles release and to guarantee harmless application, extensive screening of risks and evaluation of environmental safety should be undertaken. Also, the combination of nanomaterials with artificial intelligence and smart systems of water treatment could optimise the efficiency of the given processes, provide the opportunity to monitor them in real-time, and guide adaptive control policies. Such will play a significant role in promoting eco-friendly and smarter water treatment systems.

10. CONCLUSION

The application of iron oxide nanomaterials has emerged as an effective method for the removal of heavy metals in the aqua regia. Their distinctive physicochemical characteristics, such as large surface area, magnetic, and surface chemistry, make them useful in adsorptions and can be recovered easily. These materials are quite promising in various contaminants and environmental conditions and can be used in a variety of water treatment practices. Although these materials demonstrate promising performance, their broad application is still hindered by challenges such as scalability, long-term stability, and environmental safety concerns. Overcoming these issues will demand further research and development in synthesis techniques, surface modification, and system integration approaches to allow their effective and sustainable deployment in large-scale water purification.

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Conflict of Interest

The authors declare no conflict of interest in the publication of this article.

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