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A Comprehensive Review on Iron Oxide and Iron Oxide-based Nanomaterials for Wastewater Treatment

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ABSTRACT

The growing need for water and the increase in wastewater generation globally demand efficient water treatment processes. Conventional water remediation efforts are insufficient to meet current water treatment requirements. Nanomaterial water remediation has shown promising results and needs to be explored on a larger scale to address these issues. The most recent focus has been on composite nanomaterials made of iron oxide magnetic and superparamagnetic NPs, which have attracted considerable interest owing to their desirable characteristics, including excellent after-use recovery, targeted quality, and affordability. Iron oxide-based nanomaterials can remove organic and inorganic contaminants in multiple ways. In addition, several nanocomposites have been employed to improve their performance and incorporate novel advantageous characteristics. Chemical, green, and biological processes are used to produce these materials. Synergistic properties for water cleanup have been demonstrated using various iron-based nanocomposites. Various mechanisms of pollution removal, such as adsorption, desorption, photocatalysis, and flocculation/coagulation, have been targeted during the design of NPs. The types of water pollutants, choice of remediation methods, and various methods required for QC and the efficiency of these nanomaterials were reviewed. This review discusses various methods for preparing magnetic nanoparticles, their composite materials, the mechanism of pollutant removal, and recent applications exploring synergistic behavior for pollution removal for efficient water remediation. Issues such as safety, toxicity, removal after use, and disposal of these materials are also discussed. This manuscript provides a quick overview of iron oxide nanomaterials as a reference for advancing further studies in this area. We plan to contribute to the production bibliography of various aspects of iron-based nanomaterials for water and wastewater treatment.

INTRODUCTION

Water covers more than 70% of the Earth's surface, and only 2.5 percent of it can be consumed by humans. Many people do not have access to potable water. Of the world's population, almost 2 billion people (26 %) do not have access to clean drinking water. Conversely, two to three billion people globally experience water shortages for at least one month of the year. Two to three billion people globally experience water shortages for a few weeks each year. The number of people experiencing water problems is predicted to rise from approximately 930 million in 2016 to 1.7–2.4 billion by 2050, raising concerns about water scarcity. The environment and human livelihoods are significantly impacted by water scarcity. The depletion of freshwater resources due to pollution is a major contributor to water shortages, a pressing problem on a global scale. When water sources are polluted, they become unusable for human consumption, agricultural irrigation, and industrial processes. The reuse and treatment of wastewater, as well as other

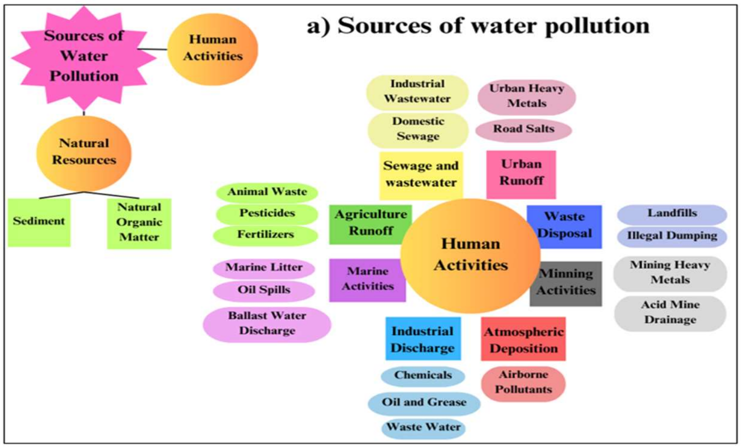

Fig. 1 (a): Various types of water pollution sources.

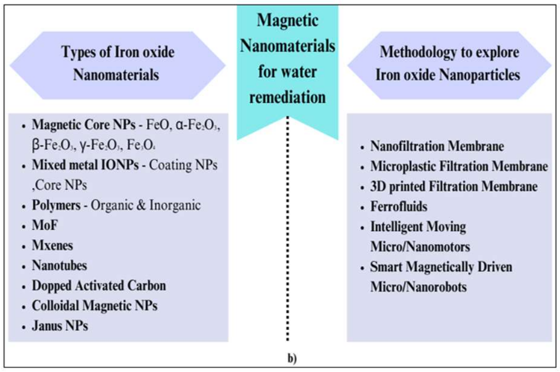

Fig. 1 (b): Various types of iron oxide nanomaterials and their methodologies used for W&WT.

clean water reuse programs, can help reduce the effects of pollution and water scarcity (Bonazzi 2023, Borah & Chetia 2023). Various types of water pollution sources, iron oxide nanomaterials (IONMs), and methodologies used for W&WT are presented in Fig. 1 a and b.

Traditionally, liquid distillation, anion exchange, ultrafiltration, reverse osmosis, activated carbon adsorption, deionization, and ultraviolet (UV) filtration are typical techniques for treating water and wastewater to remove As. These traditional wastewater treatment methods are not only costly but also energy-intensive, consuming approximately 2-3% of the energy used in water treatment, particularly in biological wastewater treatment facilities. This has created an urgent need for low-cost, sustainable, robust, and efficient solutions for wastewater treatment, which should involve minimal use of energy resources and chemicals and have low direct or indirect effects on the environment and human life (Borah & Chetia 2023).

Nanomaterials have shown great promise in addressing water and wastewater treatment problems because of their capacity to eliminate a variety of contaminants. Numerous nanomaterials have been studied and found to be useful for removing a range of contaminants from water, such as heavy metals, organic pollutants, inorganic anions, and microorganisms. Photocatalytic degradation and adsorption are the most preferred water and wastewater treatment (W&WT) methods because of their low operating costs, environmentally friendly nature, and efficacy. The most adaptable, durable, simple to prepare, and highly stable NPs investigated for W&WT are metal oxide NPs (MONPs). Iron oxide MNOPs have been studied the most for this purpose and have a wide range of applications (Campos et al. 2015). Magnetite (Fe_3O_4), hematite (α-Fe_2O_3), β-Fe_2O_3, maghemite (γ-Fe_2O_3), and wustite (FeO) are among the several nanocrystal forms of iron oxide. Hematite (α-Fe_2O_3) is the most durable state of iron oxide under ambient conditions among the various crystalline formations.

The wide applications of α-Fe_2O_3 are derived from its superior physical and chemical properties, and it can be tailored to various morphologies, particle dimensions, and heterostructures (Santhosh et al. 2019a). The

Table 1: Most used IONPs, their properties and applications. (Jojoa-Sierra et al. 2022, Jjagwe et al. 2023, Keshta et al. 2024, Muthukumar et al. 2024, Lin et al. 2018, Mohamed et al. 2017, Razzouki et al. 2015).

Chemical formula	Common name	Color	Crystal system	Type of magnetism	Water remediation application of magnetic iron-based Nanomaterials (MINMs)
α- Fe_2O_3	Hematite	Red	Rhombohedral hexagonal	Weakly ferromagnetic	(i) Adsorptive removal of organic and inorganic pollutants, microorganisms, oils, etc. (ii) Catalytic degradation of organic pollutants (dyes, chemicals, pharmaceuticals, oil spills, etc) and anti-biofouling effect. (iii) Coagulation /flocculation-based removal of microbes, oil droplets, etc. (iv) Recovery and biodegradation of crude oils. (v) Pollutant separation by membrane filtration process assisted by MINMs.
γ- Fe_2O_3	Maghemite	Red-brown	Cubic or tetragonal	Ferrimagnetic	
Fe_3O_4	Magnetite	Black	Cubic or tetragonal	Ferrimagnetic	
FeO	Ironmonoxide, wustite	Back	Black pigment	Weakly ferromagnetic	
FeOOH	Iron oxy-hydroxide	Yellow	Hexagonal, orthorhombic, and cubic	Weakly ferromagnetic or superparamagnetic	
α-FeOOH	Goethite	Yellow	Orthorhombic	Ferrimagnetic	
$Fe(OH)_3$	Iron(III) hydroxide	Reddish-brown	Different crystalline structures	Paramagnetism	

nanomaterials based on Fe_2O_3 include nanoparticles, nanotubes, nanosponges, nanocomposites with organic and inorganic materials, MXenes, and metal oxide frameworks (MOFs). These nanomaterials work through adsorption, photocatalysis, coagulation, and flocculation. These are fabricated using various chemical, hydrothermal, and sol-gel methods to improve their properties (Tao et al. 2021). Iron oxide nanoparticles explored as a basis for Magnetic Iron-based Nanomaterials (MINMs) are summarized in Table 1.

The unique characteristics of nanoparticles influence their selection, and the current state of nanoparticle research considers all their potential uses. This study is innovative because it uses a novel strategy to precisely regulate nanoparticles, thereby filling a gap in our understanding and pushing the boundaries of W&WR. This study also summarizes the applications of MINMs in contemporary nanotechnology and delves deeper into the knowledge gap by examining current trends in nano-synthesis. Furthermore, the restrictions on the use of iron-based nanoparticles for the elimination of contaminants are highlighted. The use of nanotechnology in water purification is thoroughly examined in this review, with a focus on iron oxide nanoparticles. Despite this, owing to their desirable qualities, iron-based nanoparticles require extensive research and evaluations. In this review, we examine iron-based nanoparticles and assess their key features, manufacturing methods, and ability to remove various contaminants from wastewater. In this era of prioritizing sustainable development and environmental

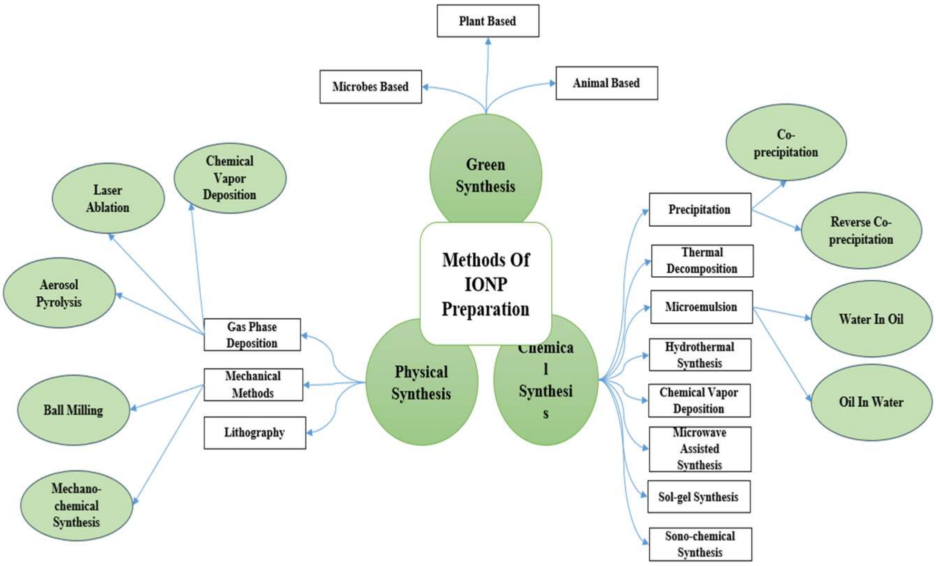

Fig. 2: Methods of iron oxide nanoparticle synthesis.

protection, the application of nanomaterials will be crucial in ensuring a safer, more sustainable, and cleaner future for industrial wastewater treatment.

METHODS OF SYNTHESIS OF IRON OXIDE-BASED NANOMATERIALS

High-quality iron oxide nanoparticles can be synthesized using various techniques, such as co-precipitation, hydrothermal synthesis, microemulsion, sonochemical synthesis, and thermal decomposition (Teja & Koh 2009). Considering modern scientific advancements, the selection of a suitable method and relevant process parameters for obtaining IONPs with desired characteristics, such as crystallinity, size, morphology, colloidal stability, polydispersity, porosity, zeta potential, and morphology, is possible. The qualities are significantly affected by the selected method of preparation and reaction parameters. The three main categories of IONP preparation techniques are physical, chemical, and biological methods (Fig. 2). The methods of preparation of iron oxide nanomaterials (IONM) and their merits and demerits are summarized in Table 2.

Co-Precipitation and Reverse Co-Precipitation

These are among the most widely utilized methods for synthesizing IONPs. Usually, it is performed using $FeCl_2$ and $FeCl_3$ along with a base such as NaOH or KOH, ammonium hydroxide, etc., at a higher temperature. Here, the oxide is formed by the dehydration of hydroxides, which later form a precipitate (Rangarajan et al. 2014). Ammonium hydroxide, deionized water, and hydrated ferric chloride were the chemical reagents used in co-precipitation to create iron oxide nanoparticles. Ionization of the chemical reagents at different temperatures while vigorously churning them in the presence of nitrogen gas yielded magnetite crystals. Therefore, the simplicity, rapid synthesis at low temperatures, and energy efficiency of the co-precipitation method make it superior to alternative biochemical methods for synthesizing iron oxide nanoparticles.

Reverse Co-Precipitation Technique

By using an active reduction reagent as a stabilizer, Estelrich et al. (2015) effectively carried out a reverse chemical co-precipitation synthesis of magnetite (Fe_3O_4) NPs. The

Table 2: Methods of preparation of Iron oxide nanomaterials (IONM) and their merits and demerits.

Preparation Method	General properties of prepared IONMs	Iron oxide nanomaterials (IONM) preparation method	
		Merits	Demerits
Co-precipitation	Size- 3 to 100nm, Shape- Spherical	• High yield of IONPS • Approved by the FDA as a contrast agent for MRI	• Difficult to control the size of NPs due to agglomeration • pH has to be maintained high
Reverse co-precipitation	Size- <100nm, Shape- Spherical	• Homogenous distribution • Control over particle properties	• Agglomeration • Environmental concerns
Microemulsion	Size- 4 to 50 nm, Shape- Spherical and Cubic	• Precipitation occurs in nano-drops • The initial reagent conc. The drop size can be utilized to control the IONPS size. • Nanoparticles have homogenous shapes and sizes	• Low yields obtained in comparison with co-precipitation • Purification is complicated.
Sol-Gel method	Size- Less than 50 nm, Shape: Various Shapes	• High purity of nanoparticles • Scalability	• Time consuming • Residual solvents • Crack formation • High permeability
Sono-chemical method	Size- 20 to 80 nm, Shape- Variable	• Fast reaction rate • Reduced solvents • Simple setup	• Scale-up challenges • Heat generation
Microwave-assisted synthesis	Size- 4 to 50 nm, Shape- Spherical	• Control over properties such as temperature and irradiation time, which can influence size and morphology • Rapid and uniform particles having high magnetic saturation	• Chances of non-uniform heating • Limited reaction monitoring
Green Synthesis	Size- 10 to 50 nm, Shape- Spherical	• Ecofriendly • Nontoxic, safer end products • Cost-effective good scalability	• Standardization inconsistency • Lower yield and purity • Unknown mechanism
Hydrothermal	Size- 2 to 1000 nm, Shape- Various shapes	• Good crystallinity • Controlled agglomeration • Medium to high yield	• Scale-up challenges • Equipment maintenance

characteristics of the uncoated and dimethyl sulfoxide (DMSO)-coated Fe_3O_4 and Fe_3O_4 NPs were compared. XRD and SEM were used to examine the microstructural and mineralogical characteristics of both samples. The findings showed that the DMSO-coated sample particles outperformed the untreated Fe_3O_4 nanoparticles in the Fourier analysis and SEM inspection. When using base materials with a varied range of reactant rates, reverse co-precipitation and co-precipitation procedures have consistency problems, require a long time, and can introduce foreign particles into the metal matrix structure of the IONPs. When using base materials with different reactant rates, co-precipitation and reverse co-precipitation techniques have challenges with repeatability and can introduce foreign particles into the metal matrix structure of the iron oxide nanoparticle result (Ogbezode et al. 2023).

Microemulsion

This procedure uses a surfactant, a polar phase, and a nonpolar phase. was used to prepare the microemulsion. The polar phase consists of metal salts, whereas the non-polar phase consists of hydrocarbons. The growth of NPs can be well-regulated using this method. Microemulsions can be of two main types: oil-in-water and water-in-oil (Darbandi et al. 2012) (Table 2).

Biological/Green Synthesis

Chemical methods are considered hazardous and energy-intensive. There has been an increase in the demand for the eco-friendly production of nanoparticles. Here, plants or microbes can be used to synthesize nanoparticles along with metal precursors. Karpagavinayagam and Vedhi 2019 used *Avicennia marina* flowers for the synthesis of IONPs. $FeCl_3$ was added to the flower extract and centrifuged to obtain nanoparticles. The particle size was approximately 45 nm. Baaziz et al. 2014 used a biochemical strategy to develop iron oxide nanoparticles in coated sand. The study's goal was to solve water treatment-related difficulties by biochemically producing and characterizing iron oxide nanoparticles from coated sands. El-Sheekh et al. (2021a) used extracts of different algae to biosynthesize IONPs using $FeCl_3$ as an iron precursor. The size range of these IONPs prepared from different extracts was found to be between 5 and 35 nm.

Microwave-Assisted Synthesis

Aivazoglou et al. (2018) performed IONP synthesis using microwave radiation, where the metal precursors are heated along with a base that produces metal oxides such as NaOH or NH_4OH. This method produces a high concentration of nanoparticles at a faster rate than other methods.

Heat Treatment/Thermal Decomposition Technique

In general, iron oxides can be heated to temperatures higher than 250°C, and nanomaterials can be produced using the thermal breakdown heat treatment approach (Ogbezode et al. 2023).

Lithographic Technique

The lithographic process is a physical technique employed for nanoparticle production and is known to be both costly and energy-intensive. Despite these challenges, it is widely used to create nanomaterials for various applications in electronic devices and computer accessories (Seyedi et al. 2015). As a top-down approach, lithographic synthesis is suitable for generating micro- and nanoparticles. Various methods, including fusion-ion, nano-imprint, dip-print, electron beam lithography, and photolithography, are used in this process. These techniques have broad applications, notably in additive manufacturing and the semiconductor industry (Kayani et al. 2014).

Large-Scale Synthesis of IONP-Based Nanomaterials

The key problems in large-scale Fe_3O_4 nanoparticle production are as follows: the degree of uniformity and repeatability between batches, expenses, efficiency, environmental concerns, and sorption capability. To address the problem of reproducibility across batches and determine the ideal conditions for the effective removal of pollutants, particle size distribution, and purity, they must be closely tracked, and reaction parameters, such as pH, temperature, and reactant concentrations, must be precisely controlled. However, there are major obstacles to the large-scale manufacture of these nanoparticles, which limit their economic viability and real-time applications. However, typical materials for Fe_3O_4 production may be expensive and inefficient for large-scale applications. In addition, several synthesis processes used to produce high-quality magnetite nanoparticles are expensive and time-consuming. For example, the use of surfactants, organic solvents, and other additives to promote uniform particle formation and reduce agglomeration has been shown in numerous studies to significantly increase the total cost of synthesis. To address this issue, green synthesis is a viable method for creating Fe_3O_4 nanoparticles from sustainable resources (Keshta et al. 2024a).

MAGNETIC IRON OXIDE NANOCOMPOSITES MATERIALS

Functionalization of iron oxide nanoparticles (IONPs) is vital for improving their applicability in wastewater treatment because of innate difficulties such as rapid aggregation, poor dispersibility in water, and limited pollutant selectivity. Functionalization addresses these issues by modifying the nanoparticle surfaces with chemical groups, polymers, and coatings. Chemical groups like EDTA, GSH, and PAA, and polymers such as chitosan and Poly(N-isopropyl acrylamide) (PNIPAM), enhance stability, dispersibility, and surface properties, while coatings like silica and graphene stabilize IONPs, prevent aggregation, and improve catalytic and adsorption capabilities in both homogeneous and heterogeneous systems. The surface functionalization of IONP and their composite materials is shown in Fig. 3a, and GSH functionalization is shown in Fig. 3b. Functionalized IONPs exhibit improved catalytic activity, effectively degrading pollutants and enhancing the wastewater treatment efficiency. Functionalization offers tailored solutions to address the challenges associated with unmodified IONPs, making them indispensable tools in modern environmental remediation. Surface functionalization can be achieved by in situ processes and post-synthesis functionalization of IONPs. Some frequently utilized magnetic sources are listed in Table 3.

***In situ* surface functionalization of Fe_3O_4:** This involves the direct functionalization of groups during synthesis. Depending on the intended use, this process can alter the chemical, physical, or biological characteristics of the food. This contributes to the advancement and broadening of the applications of nanoparticles (Popescu et al. 2019). De Tercero et al. 2013a and Popescu et al. 2019 demonstrated the in situ functionalization of IONP, where alkyne groups were functionalized in IONPs by a continuous process called click reactions. This process imparts an inorganic core and an organic shell to the nanoparticles, thus widening the scope of their applications in various fields. Karimzadeh et al. 2017 performed synthesis and surface coating of superparamagnetic nanoparticles with polyethyleneimine (PEI) and polyethylene glycol (PEG). The surface coating was performed using the Cathodic Electrochemical deposition (CED) process. The surface coating enhanced the physicochemical and magnetic properties essential for biomedical applications.

Post-synthesis surface functionalization of Fe_3O_4: Post-synthesis surface functionalization is a process

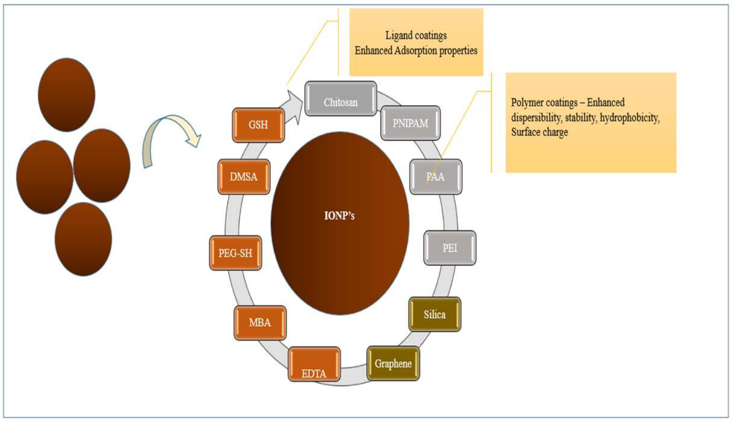

Fig. 3 (a): Surface functionalization: Various surface functionalization agents used for IONP.

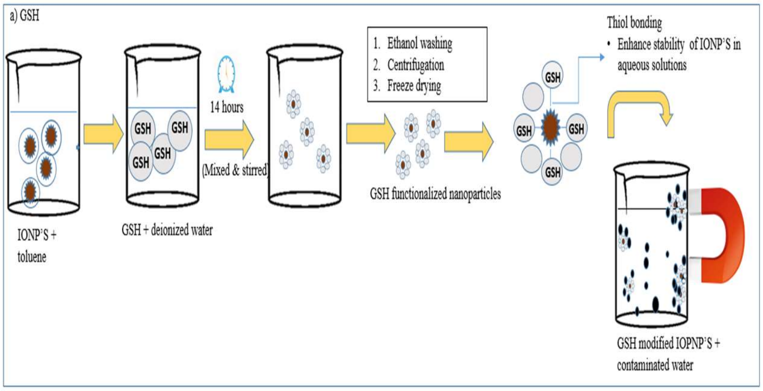

Fig. 3 (b): Surface functionalization: Schematic of IONP functionalization with GSH.

Table 3: Some frequently utilized magnetic sources.

Source	Iron oxide (type)	Particle size	Solvent/Temperature [°C]/Time [min.]	Value for magnetic saturation [emu.g^{-1}]	References
$FeCl_3$, $FeSO_47H_2O$	Magnetite	13 nm	Water/80/20	74	(De Mello et al. 2019)
$FeSO_{47}H_2O$, $FeCl_{36}H_2O$	Magnetite	10-50 nm	Water/65/15	-	(Klencsar et al. 2019)
$Fe(NO_3)_{39}H_2O$	Hematite	24 nm	Ethanol/79/60	0.71	(Nguyen et al. 2020)
$FeCl_{36}H_2O$	Ferrite	20-40 nm	Water/--/60	148	(Peng et al. 2017)
$FeCl_3$, $FeSO_{47}H_2O$	Magnetite	25 nm	Water/40/120	14.46	(Sundararaman, et al. 2020)
$FeCl_3$	Magnetite	5 nm	Ethylene glycol/100/30	49.7	(Radon et al. 2020)
$FeCl_{36}H_2O$, $FeCl_{24}H_2O$	Magnetite	12.5 nm	Water/70/40	69.2	(Li et al. 2017)
$Fe_2(SO4)_{35}H_2O$/ $FeSO_{47}H_2O$	Magnetite	50-75 nm	Water/70/30	10.40	(Andrade Neto et al. 2020)
$Fe_3(CO)_{12}$	Magnetite	3 nm	Water/450/40	-	(Vangelista et al. 2012)

used to modify already synthesized IONPs with different functional groups, chemicals, or coatings. This will help customize and impart desired properties to nanoparticles, thus increasing the range of their applications. In the post-synthesis functionalization process, mesoporous guanidine-functionalized Santa Barbara Amorphous-15 (SBA-15)/ Fe_3O_4, that is, (Fe_3O_4@SBA-15-Gd), was designed. In situ magnetization using Fe_3O_4 nanoparticles was achieved (Fe_3O_4@SBA-15). The composites were then modified with 3-aminopropyltriethoxysilane (APTES) to get Fe_3O_4@ SBA-15-NH_2. This was followed by nucleophilic addition to cyanimide to obtain magnetic nano-adsorbent NPs (Fe_3O_4@ SBA-15-Gd) and used successfully for decontamination of aqueous solutions from Pb(II) and Cu(II) (Hassanzadeh-Afruzi et al. 2023, Rosaline et al. 2024).

Types of Functionalization

Functionalization is achieved using various chemical groups and ligands, polymers, and inorganic materials. Conversely, IONPs can be doped with other materials, such as activated carbon, for improved performance.

Chemical Groups and Ligands

EDTA: Ethylene diamine tetraacetic acid (EDTA) functionalized iron oxide nanoparticles represent a significant advancement in wastewater treatment technologies, offering enhanced performance, ease of recovery, and sustainability, particularly in heavy metal ion removal (Kobylinska et al. 2020a, Ramos-Guivar et al. 2021, Fumis et al. 2022). EDTA modification enhances the adsorption properties of nanoparticles by introducing additional chelating sites, thereby increasing the affinity and selectivity for metals such as Cr (III), Zn (II), Pb (II), Cu (II), and Cd (II), and boosting the overall adsorption capacities. These nanoparticles exhibit rapid kinetics and efficiently remove contaminants from water within short contact times (Kobylinska et al. 2020a). EDTA-functionalized iron oxide nanoparticles have demonstrated robust stability owing to a protective silica shell, enhancing their thermal stability against oxidation processes that could compromise their effectiveness in water treatment applications (Fumis et al. 2022). This stability ensures prolonged performance and reliability during multiple adsorption-desorption cycles, making them economically viable and sustainable options for environmental remediation (Ramos-Guivar et al. 2021, Fumis et al. 2022).

The intrinsic magnetic properties of these nanoparticles facilitate their separation from water after adsorption using external magnetic fields, streamlining the recovery procedure and allowing repeated use without significantly reducing their effectiveness. Experimental information from numerous studies has validated the efficiency of EDTA-functionalized IONPs in real-world scenarios, showcasing high removal efficiencies and accurate recoveries across various water samples. Advanced kinetic and adsorption isotherm models further elucidate the mechanisms underlying their adsorption behavior, highlighting chemisorption as the predominant mechanism owing to strong EDTA-metal ion interactions (Kobylinska et al. 2020a, Ramos-Guivar et al. 2021), underscoring their potential as effective nano-adsorbents for addressing water pollution challenges posed by heavy metal ions, and supporting their integration into practical environmental remediation strategies (Ramos-Guivar et al. 2021).

Glutathione (GSH): The integration of magnetic separation with GSH-functionalized iron oxide nanoparticles provides significant advantages for water treatment applications. Superparamagnetic iron oxide nanoparticles (SPIONs) were first synthesized and coated with oleic acid in toluene to ensure stability. GSH was separately dissolved in water, and mixing SPIONs with the GSH solution displaced oleic acid via coordination bonds during stirring. Centrifugation was used to separate the GSH-coated SPIONs, after which excess GSH was removed using an ethanol wash, and the GSH was freeze-dried into a powder for use in applications. GSH-functionalized nanoparticles eliminate pollutants from water via various mechanisms, such as electrostatic attraction, hydrogen bonding, and π-interactions between GSH moieties and contaminants, which promote their adsorption onto the nanoparticle surface. The functionalization of IONPs with GSH is shown in Fig. 3b.

The magnetic and adsorption properties of GSH-functionalized nanoparticles make them particularly effective for removing contaminants from water, making them efficient and cost-effective alternatives to conventional methods (Tariq et al. 2022). Additionally, Behera et al. (2022) demonstrated the enhanced sensitivity and stability of GSH-functionalized nanocomposites for detecting nitrophenol isomers. Characterization techniques confirmed the formation of structured ▯- Fe_2O_3 and underscored the electrocatalytic activity, conductivity, and wide detection range of the nanocomposites. These findings highlight the pivotal role of GSH in augmenting sensor performance by facilitating improved electron transfer kinetics and providing a larger surface area for enhanced interaction with analytes, signifying the benefits of GSH functionalization in enhancing the capabilities of iron oxide nanoparticles for wastewater treatment applications, particularly in improving sensing efficiency and overall effectiveness in environmental remediation efforts (Behera et al. 2022).

Polymer Coatings

In general, polymer Coatings of NPs offer various advantages, such as improved W&WT efficacy, enhanced stability, and increased porosity and surface area of IONPs.

Chitosan: Chitosan-coated nanoparticles improve wastewater treatment efficacy by enhancing the stability and increasing the porosity and surface area of IONP. They are effective in the photocatalytic removal of pollutants, including dyes and mercury, from aquatic environments because of their high water permeability and antibacterial properties. Additionally, the ease of chemical modification and the robust nature of chitosan enhance the stability and efficiency of these nanoparticles in wastewater treatment applications (Ismail et al. 2023). These properties facilitate strong electrostatic interactions with anionic dyes, such as Evans Blue (EB) and Acid Yellow 25, resulting in high-capacity adsorption even under continuous flow conditions, as demonstrated in chromatography setups (Ismail et al. 2023). FeO_4 nanoparticles' magnetic characteristics make it simple to separate them from treated water using an external magnetic field, making the procedure effective and simple. Moreover, the biocompatibility and biodegradability of chitosan make it an environmentally sustainable choice for such applications, offering a promising eco-friendly solution for removing pollutants from wastewater (Lee et al. 2019, Rehman et al. 2024).

The preparation methods for these functionalized nanoparticles typically involve chitosan dissolving in acetic acid, combined with iron oxide nanoparticles, stirring for an extended period, and then magnetically collecting, washing, and drying (Gómez Pérez et al. 2020). These coatings significantly enhance the ability of nanoparticles to adsorb heavy metal ions owing to the chemical and biological characteristics of chitosan. Modifications of chitosan, such as the introduction of functional groups, further improve its adsorption capacity and selectivity for metal ions, making it highly effective for removing toxic substances such as Cr (VI) from aqueous solutions (Khalil et al. 2020).

PNIPAM: PNIPAm is a thermoresponsive polymer known for its phase-transition behavior triggered by temperature changes, shifting from a hydrophilic to a hydrophobic state at approximately 32°C. This characteristic phase transition, in which polymer chains collapse owing to altered hydrogen bonding with water molecules within a cross-linked network, makes Poly-N-isopropyl acrylamide highly advantageous for various applications, including wastewater treatment. Its ability to undergo substantial volume phase transitions (VPTs) in response to minor temperature adjustments allows for precise control over the adsorption and removal of organic compounds from aqueous environments (Lu et al. 2016). PNIPAm-functionalized nanoparticles exhibited enhanced performance in treating emulsified oily wastewater by leveraging their thermoresponsive nature. This property enables nanoparticles to adjust their hydrophobicity based on temperature variations, thereby optimizing the adsorption and separation processes for contaminants (Tao et al. 2020). Utilizing PNIPAm-grafted iron oxide nanoparticles can improve the efficiency and efficacy of pollutant removal in wastewater treatment systems, highlighting PNIPAm's potential as a versatile and effective material for environmental remediation. In wastewater treatment strategies, PNIPAm has been effectively utilized to functionalize iron oxide nanoparticles (MIO@SiO_2-PNIPAM) through a "grafting through" approach involving MPS-modified MNPs and NIPAM monomers (Tao et al. 2020).

Polyacrylic acid (PAA) considerably increases the efficacy of iron oxide nanoparticles (IONPs) in wastewater treatment, especially in the elimination of ions from heavy metals such as Pb (II). This was achieved through surface adsorption and ligand exchange methods (Fig. 4a). Magnetic chitosan (MCS-PAA) nanoparticles were prepared by first activating polyacrylic acid (PAA) carboxyl groups with EDC and NHS in water, followed by conjugation with magnetic chitosan (MCS) through amide bond formation over 24 h. After isolating the resultant nanoparticles with a magnet, washing them with deionized water, and drying them, a stable MCS–PAA composite suitable for wastewater treatment applications was produced. (Fig. 4b), PAA functionalization effectively boosted the adsorption capacity of IONPs by chelating pollutants via abundant carboxyl groups. This modification enhances the stability and dispersibility of IONPs in aqueous environments, ensuring their robust performance under the acidic conditions typical of wastewater. Covalently bonding PAA to magnetic chitosan surfaces further enhances the durability and acid resistance of the composite material, which is crucial for sustained pollutant removal processes (Mdlovu et al. 2020, Nordin et al. 2021). The successful application of PAA-functionalized IONPs demonstrates their high adsorption capacities, efficient kinetics, and favorable isotherm models, highlighting their potential as advanced materials in wastewater treatment technologies.

Moreover, PAA's compatibility with chitosan enhances the overall environmental applicability of these nanocomposites, supporting their role in sustainable water purification processes. This synergistic approach not only improves the performance and stability of IONPs but also ensures their biocompatibility and recyclability, making them suitable for long-term use in treating contaminated water sources. By leveraging PAA's properties through methods such as in situ synthesis and layer-by-layer assembly, researchers can tailor IONPs for specific pollutant removal applications, further advancing the field of wastewater treatment (Shair et al. 2021). Overall, PAA-functionalized IONPs represent a promising advancement in environmental remediation, offering efficient, reliable, and environmentally friendly solutions for addressing global water pollution challenges.

PEI: Polyethyleneimine (PEI) functionalization has significantly enhanced the efficiency of adsorbents in wastewater treatment, improving their adsorption capacity, stability, and recyclability (Shair et al. 2021, Yan et al. 2023). PEI-functionalized magnetic nanoparticles (MNPs) have proven effective in removing heavy metals such as Pb (II) under various conditions, with adsorption behavior fitting pseudo-second-order kinetics and Langmuir

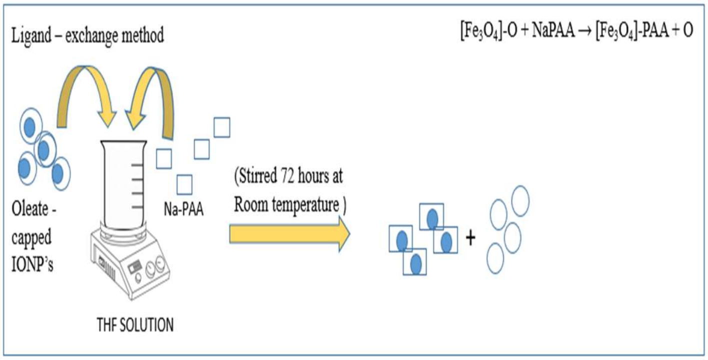

Fig. 4 (a): Polyacrylic acid (PAA) functionalization: Ligand exchange PAA activation method.

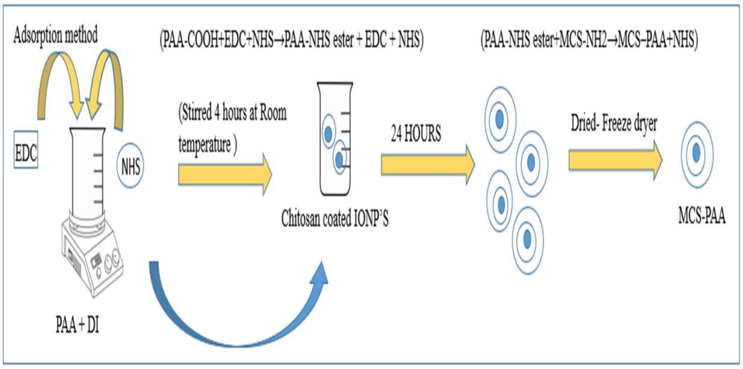

Fig. 4 (b): Polyacrylic acid (PAA) functionalization: Absorption PAA activation method.

isotherm models (Shair et al. 2021). This indicates strong monolayer adsorption, and these nanoparticles maintained their performance after multiple reuse cycles, highlighting their durability and cost-effectiveness. In dye removal, PEI-functionalized cellulose with magnetic nanoparticles (MCPEI) shows a high adsorption capacity for anionic dyes, offering a simpler and more efficient alternative to traditional activated carbon (Yan et al. 2023).

PEI-coated zero-valent iron nanoparticles are highly effective in treating hexavalent chromium (Cr(VI))-contaminated water, reducing Cr(VI) to Cr(III), which is less toxic, while maintaining structural integrity. This makes them suitable for in situ remediation of Cr-contaminated groundwater (Mardikar et al. 2021). PEI functionalization significantly enhances the adsorption properties of various nanoparticles, making them versatile and practical for diverse wastewater treatment applications. These advancements suggest that PEI-functionalized materials can play a vital role in improving the effectiveness and sustainability of wastewater treatment processes. PEI-functionalized cellulose with magnetic nanoparticles (MCPEI) exhibits a high adsorption capacity for anionic dyes, presenting a simpler and more effective alternative to traditional activated carbon (Sachan et al. 2021). PEI-coated Fe_3O_4 with β-cyclodextrin (Fe_3O_4@PEI@β-CD) demonstrates high efficiency in demulsifying oily wastewater, achieving over 95% separation under various conditions and retaining its performance after multiple recycling cycles. These advancements indicate that PEI-functionalized materials are versatile, practical, and environmentally friendly solutions for diverse wastewater treatment applications, enhancing efficiency and sustainability (Jain et al. 2018a, Seth et al. 2019).

Surface Coating of IONPs with Inorganic Materials

IONPs are coated with inorganic materials such as graphene and silica coatings, metal oxides, metal sulfides, and clay nanocomposites. These composite materials exhibit enhanced W&WT performance through various mechanisms, such as enhanced photoactivity under visible light, increased stability, dispersibility, and functionality.

Graphene: Graphene oxide (GO) has attracted noteworthy interest owing to its distinct characteristics, making it an ideal candidate for various applications, including wastewater treatment. When GO is combined with iron oxide nanoparticles, the resulting composite material exhibits enhanced performance in the removal of contaminants from water. The oxygen-containing functional groups present in GO, such as epoxy, hydroxyl, carboxyl, and carbonyl groups, facilitate the attachment of metal oxide nanomaterials, thereby improving the adsorptive and photocatalytic properties of the composite (Maji et al. 2018). This functionalization also enhances the stability and dispersion of iron oxide nanoparticles, preventing agglomeration and increasing the surface area available for interaction with pollutants (Kumar et al. 2019). Additionally, the GO coating shifts the absorption threshold to the visible region, enhancing the photoactivity and enabling effective photocatalytic processes under visible light (Wang et al. 2019). This modification not only improves the thermal and chemical stability of the composite but also enhances its reusability and longevity, making it a robust and efficient solution for industrial wastewater treatment (Khan et al. 2016). The synergistic effects of GO and iron oxide nanoparticles address the need for high-performance, cost-effective, and sustainable treatment technologies (Weng et al. 2018). These advancements underscore the potential of GO-based composites to revolutionize wastewater treatment applications (Lingamdinne et al. 2019).

Silica: Functionalizing IONPs with silica significantly enhances their stability, dispersibility, and functionality for various applications, including catalysis and environmental remediation. The primary approaches to achieve this include the hydrolysis and condensation of silica precursors in sol-gel processes and Stöber synthesis, which produces uniform silica coatings via controlled hydrolysis in an alcohol-water mixture. Additionally, surface modification techniques, such as salinization, attach silane coupling agents to nanoparticle surfaces, creating a silica layer. These methods ensure a robust and uniform silica coating, improving the resistance of nanoparticles to aggregation, their chemical stability, and their compatibility with other functional groups for targeted applications. Andolsi et al. 2023 prepared and characterized surface-coated Fe_3O_4 nanocomposite and explored for crystal violet (CV) dye removal. In this study, separately prepared Fe_3O_4 and SiO_2 NPs were prepared, and a magnetite coating of silica Fe_3O_4 /SiO_2 was performed. Process optimization was performed for the removal of CV from solution; the effects of solution pH, concentration of the adsorbent, exposure time, and ionic strength were evaluated.

Metal nanoparticle coating: Fe_3O_4 surfaces are coated with metals to create an inert and protective layer on them. Fe_3O_4 surfaces, as such, are less amenable to functionalization than metal-coated surfaces. Gold nanoparticles (Au NPs) are commonly used to coat Fe_3O_4 because of their strong interactions with sulfur-containing compounds. One method involves the reduction of $HAuCl_4$ onto Fe_3O_4 nanoparticles, as reported. Xia et al. 2011prepared a Fe_3O_4@C@Ag composite for use in medication delivery, MRI applications, and antibacterial therapies.

Metal oxides/sulfides: Coating Fe_3O_4 with metal oxides or sulfides imparts unique chemical and physical characteristics.

Fe_3O_4@ZnO nanoparticles were produced by Hong et al. in 2008. via the direct precipitation of zinc acetate and ammonium carbonate. These functionalized nanoparticles exhibited improved antioxidant properties compared to bare Fe_3O_4.

Magnetic iron oxide-clay nanocomposites (MICNCs): Mohammed & Samaka 2018 coated natural bentonite (NB) with Fe_3O_4 NPs to obtain a coating (CB) and used it to sequester Cu(II) ions from polluted solutions. The study revealed a substantial improvement in the CB, such as its surface area, surface morphology, and mesoporous structure. A comparison analysis suggests CB as an excellent material for Cu(II) removal and practical applications for Cu(II) removal from contaminated wastewater.

Activated Carbon Doped with IONPs

Jain et al. (2018b) investigated the production of iron oxide nanoparticles (Fe_3O_4) and their composites with activated carbon (Fe_3O_4/AC) to remove harmful metal ions from water, including chromium (Cr(VI)), copper (Cu(II)), and cadmium (Cd(II)). The nanoparticles were synthesized using a straightforward chemical process and characterized using various techniques to examine their structures and properties. The study identified the optimal conditions for removing these metals, noting that an acidic environment (pH 2) was ideal for chromium, whereas a neutral pH (pH 6) was most effective for copper and cadmium. The Fe_3O_4/AC composite demonstrated particularly high efficiency, especially in removing Cr and Cu, with the adsorption data fitting well

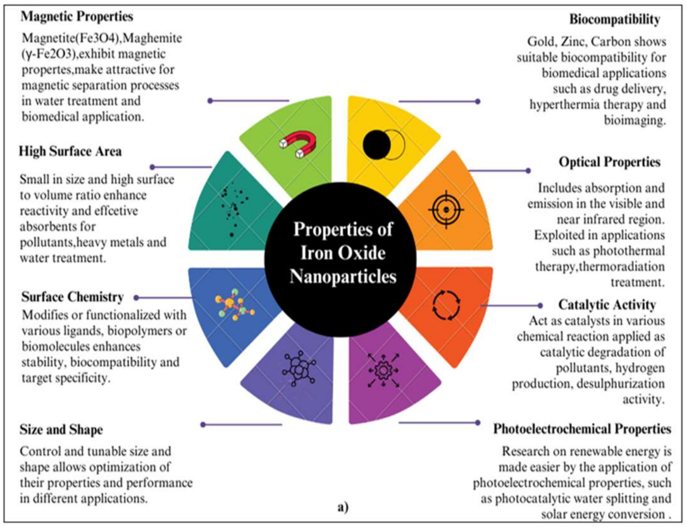

Fig. 5 (a): Useful properties of Iron oxide nanomaterials.

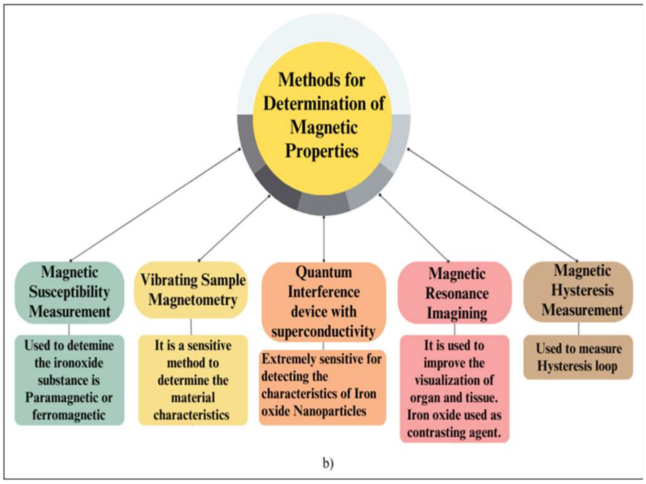

Fig. 5 (b): Methods for the determination of their magnetic properties.

with the predictive models. The study also found that the adsorption process was more effective at higher temperatures and that the nanoparticles could be regenerated and reused multiple times after treatment with acid, highlighting their potential for water purification (Jain et al. 2018a).

USEFUL PROPERTIES OF IRON OXIDE NANOMATERIALS, MAGNETIC PROPERTY MEASUREMENT, AND MAGNETIC PROPERTY FACTORS

Useful Properties of Iron Oxide Nanomaterials

The properties of IONPs encompass a wide range, including magnetic properties (Vakili-Ghartavol et al. 2020a, Arumugam et al. 2021, Keshta et al. 2024b, Atabaki 2024), high surface area, surface chemistry, size, and shape (Baalousha et al. 2008, Lassoued et al. 2017a, Nguyen et al. 2020, Niraula et al. 2021a, Vo et al. 2024), biocompatibility(Kharey et al. 2023a), optical properties (Salakhitdinova et al. 2024), catalytic activity (Bouazizi et al. 2019, Rawat et al. 2021, Ammar et al. 2021), and photoelectrochemical properties (Ben Mammar and Hamadou 2023, Lys et al. 2024). The properties of the iron oxide nanomaterials are summarized in Fig. 5a, and the equipment used for the measurement of the magnetic properties is presented in Fig. 5b.

Magnetic coercivity indicates the ability of a material to resist changes in magnetization. This also indicates how the materials withstand external magnetic fields. This property is used to classify materials as hard, semi-hard, or soft. High saturation magnetization values enable a quick response to external magnetic fields, facilitating fast separation from aqueous solutions containing heavy metals (Jain et al. 2018b). Superparamagnetic materials align with an applied magnetic field but become random when the field is removed and do not retain magnetic memory. Ferromagnetic materials (γ-Fe_2O_3) have all their electrons aligned in one direction when a magnetic field is applied to them. Even after the field is removed, they remain aligned in the same direction as the field. Ferrimagnetic materials have electrons arranged in an unequal alignment when a magnetic field is applied to them. An example is Fe_3O_4. The magnetic activity measurements were summarized as follows.

Devices for the Measurement of the Magnetic Properties of the Materials

Magnetic susceptibility measurements involve assessing a material's susceptibility to magnetization in an applied magnetic field. This test can determine whether an iron oxide substance is paramagnetic or ferromagnetic. Vibrating Sample Magnetometry (VSM) is a highly sensitive method for determining the magnetic characteristics of a material. In VSM, a sample is exposed to different magnetic fields to assess its magnetization. This method can be used to analyze the magnetic characteristics of iron oxides. Superconducting quantum interference device (SQUID) magnetometry is an extremely sensitive method for measuring the magnetic characteristics of materials with weak magnetic signals, particularly iron oxide nanoparticles. Magnetic Resonance Imaging (MRI) is a medical imaging method that utilizes the magnetic characteristics of certain atoms, such as those found in iron oxide nanoparticles, to improve organ and tissue visualization during imaging. Magnetic Hysteresis Measurement is a technique used to measure a material's magnetic hysteresis loop, which demonstrates the relationship between the material's magnetization and the applied magnetic field. This method can help identify and examine the distinctive hysteresis behaviors of iron oxide materials.

Factors Affecting Magnetic Properties of IONPs

Size and shape: The hematite nanoparticles displayed a diverse size range, spanning from 21 to 82 nm, with a gradual increment in particle size (Lassoued et al. 2017b). These nanoparticles exhibit diverse shapes, such as nanotubes, nanodiscs, and nanorods (Niraula et al. 2021b). This variability in size and morphology is expected to impart distinctive properties to the nanoparticles, rendering them highly effective for applications in magnetic separation processes for water treatment and biomedical applications.

Surface Coating: Iron oxide nanoparticles can be rendered biocompatible through various surface treatments, including the application of biopolymers and biomolecules. Interestingly, as the pH level increased, the percentage of adsorption also increased. It is important to remember that substances such as phosphatidylcholine (PC) and humic acids (HA) are frequently employed to coat iron oxide nanoparticles (Demangeat et al. 2020).

Composition of nanomaterials: Iron oxide nanoparticles (IO-Au NPs) have a significant magnetism of 65 $emu.g^{-1}$ and exhibit remarkable supermagnetic qualities. These nanoparticles have the potential to be used as theranostic agents for therapeutic and biomedical imaging (Kharey et al. 2023b). Moreover, through atomic contact, the electrochemical properties of carbon-modified iron oxide nanoparticles improve molecular biocompatibility (Verma et al. 2021).

Numerous academic articles have proposed a scientific approach for converting standard iron oxide nanoparticles (IONPs) into superparamagnetic nanoparticles using surface functionalization techniques. Overcoming the challenges of loss of magnetism and inconsistency in magnetic properties, these strategies encompass various structural designs, such as Janus-type formations, matrix dispersion, core-shell, and shell–core-shell. More precisely, the Janus structure enhances the magnetic behavior of IONPs in a magnetic force field using functionalized magnetic IONPs as stabilizing nanomaterials. He et al. (2020) found that magnetic Janus nanoparticles are efficient in removing emulsified oily waste materials from wastewater. When subjected to an external magnetic field, the asymmetrical surface wettability of the Janus NPs anchors more actively to oil droplets and removes them efficiently from oily wastewaters with uniform surface wettability. The Janus NPs showed a higher removal efficiency of 91.5% compared to magnetic carboxymethyl cellulose and ethyl cellulose nanoparticles [M-CMC-EC NPs], which was 84.3%, making Janus NPs suitable for oily waste removal. This study also highlighted the recyclability and efficiency of Janus NPs, as they are easily recyclable and reusable for frequent use without undergoing any complex regeneration process (He et al. 2020b).

The chemical process involves the destabilization of ions owing to the loss of magnetism. Various approaches have been proposed in multiple studies to address issues such as structural instability, particle aggregation, and problems with magnetic behavior (Zhao et al. 2020). The encapsulation of iron oxide microstructures with nano-coating materials is a core-shell structure. These materials stabilize the elemental core shells of iron oxide nanoparticles (IONPs) by occupying voids in their crystal structure. The crystal is supported by functional materials placed adjacent to each other on the magnetic IONPs, which also protect the core of the materials from chemical reactions. The shells of IONPs prevent unwanted chemical activity from entering the core. Another goal of this technique is to prevent the growth of small superparamagnetic nanoparticles into larger but less potent magnetic IONPs (Marcu et al. 2013, Siddiqi et al. 2016, Vakili-Ghartavol et al. 2020a).

CHARACTERIZATION OF IONPs AND NANOCOMPOSITES

Analytical studies, including adsorption kinetics, exemplified by models such as the Langmuir model, are pivotal in evaluating the efficiency of these functionalized IONPs. The Langmuir model helps understand the monolayer adsorption capacity (Qmax) and affinity (KL) of IONPs for pollutants, providing insights into surface coverage and adsorption energy (Dehbi et al. 2020). Studies on magnetic properties elucidate the behavior of nanoparticles under external magnetic fields, which is crucial for their recovery and reuse in water treatment processes (Aisida et al. 2021). These analytical approaches collectively assess the stability, dispersibility, and pollutant adsorption efficiency of nanoparticles, which are essential for designing effective wastewater treatment strategies and ensuring environmental sustainability. The comprehensive characterization of magnetic iron-based nanomaterials can be achieved using various instrumental techniques, as listed in Table 3.

Spectral methods, including UV-visible spectroscopy, FT-IR, and ICP-OES, are crucial for identifying nanoparticle formation, functional groups, and elemental compositions (Rajiv et al. 2017). X-ray diffraction (XRD) was used to analyze the crystal structure and phase composition, while X-ray fluorescence (XRF) was used to obtain detailed elemental analysis (Rajendran et al. 2023). High-resolution imaging techniques, such as Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), reveal surface morphology, size, and dispersion (El-Sheekh

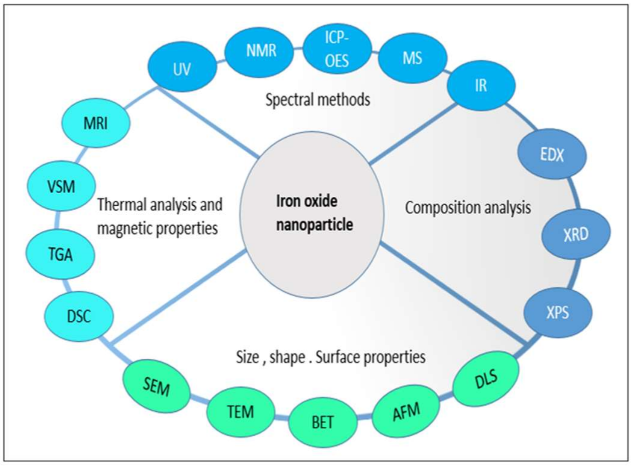

Fig. 6: Different IONP-based material characterization techniques.

Table 4: Methods for characterizing iron oxide nanomaterials.

Characterization Technique	Primary Application of the Technique	Key Material Attributes Measured
UV-visible spectroscopy	Optical Analysis	Surface Plasmon Resonance, Absorption
Infrared Spectroscopy (FT-IR)	Molecular Structure Analysis	Functional Groups, Bonding Types.
Scanning Electron Microscopy (SEM)	Morphology Study	Size, Shape, Aggregation, Surface Morphology
Transmission Electron Microscopy (HRTEM)	Detailed Morphology Study	Size, Shape, Aggregation, Lattice Structure
Dynamic Light Scattering (DLS)	Particle Size Distribution	Hydrodynamic Size, Polydispersity Index
Atomic Force Microscopy (AFM)	Surface Topography	Structure, Geometry, Distribution
Fluorescent Spectroscopy (FS)	Optical Properties	Emission, Wavelength, Optical Properties
Differential Scanning Calorimetry (DSC)	Thermal Analysis	Phase Transitions, Heat Capacity
Mass Spectrometry (MS)	Composition and Molecular Analysis	Surface Composition, Molecular Weight, Isotopic Distribution, Fragmentation Patterns
Nuclear Magnetic Resonance (NMR)	Structural and Purity Analysis	Purity, Composition, Chemical Shifts
X-Ray Photoelectron Spectroscopy (XPS)	Surface Composition Analysis	Chemical Composition, Elemental Composition
X-ray diffraction (XRD)	Crystallinity and Phase Analysis	Crystallinity, Phase Identification

et al. 2021b). The pH–Point Zero Charge (pHpzc) method assesses the surface charge characteristics. (Ha et al. 2021) When combined, these methods offer vital details about the IONPs' magnetic, chemical, and physical characteristics. These details are crucial for maximizing their use in various settings, such as industrial processes and environmental remediation. Different IONP-based material characterization techniques are presented in Fig. 6 and summarized in Table 4.

Spectral Methods: UV-visible spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) are crucial techniques for characterizing iron oxide nanoparticles (IONPs), each providing unique insights into their properties and applications. UV-visible spectroscopy identifies absorption peaks to determine the concentration, size, shape, and aggregation state of IONPs, elucidating surface plasmon resonance (SPR) in metallic nanoparticles and confirming their formation and properties within the 200–800 nm range (Rajiv et al. 2017, Yadav et al. 2023).

FTIR spectroscopy revealed the functional groups and bonding structures, highlighting the characteristic bands for Fe-O-Fe vibrational modes and interactions between organic extracts and IONPs. This also confirms dye adsorption and the presence of magnetic cores in porous magnetite nanospheres (El-Sheekh et al. 2021b, Yadav et al. 2023, Mbachu et al. 2023).

ICP-OES performs elemental analysis by utilizing high-temperature plasma to ionize samples and measuring the emitted wavelengths to quantify elements such as iron in various matrices, including plant tissues. This technique ensures accurate characterization and safety assessments in environmental, nanotechnology, and food science applications (Kobylinska et al. 2020b). Coupled with other characterization methods, ICP-OES helps optimize the synthesis parameters and enhances the understanding of iron oxide nanoparticle (IONP) behavior. Collectively, these techniques provide comprehensive insights into the properties and applications of IONPs, facilitating advancements in wastewater treatment and biomedicine.

Nuclear Magnetic Resonance spectroscopy was used to analyze the chemical structure and stability of the functionalized iron oxide nanoparticles. To confirm the effectiveness of nanoparticle functionalization and guarantee the purity of the finished product, comprehensive information on the molecular weights and composition of the stabilizing agents is required. NMR helps understand the effectiveness of different stabilization strategies by examining the structure and interactions of functionalized nanoparticles and confirming the desired chemical modifications and overall quality. Mass spectrometry, particularly Electron Impact Mass Spectroscopy (EIMS), offers significant potential for the characterization of iron oxide nanoparticles. The ability to differentiate between compounds and identify their molecular fragments highlights the effectiveness of mass spectrometry in understanding the surface chemistry and composition of iron oxide nanoparticles (Willis et al. 2005).

Methods to Determine Physical and Particle Surface Properties: Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Brunauer–Emmett–Teller (BET) analysis, and pH point zero charge (pHpzc) measurements are essential techniques for characterizing iron oxide nanoparticles (IONPs). SEM provides detailed insights into the surface morphology, aggregation state, and elemental composition, revealing spherical nanoparticles that form aggregates owing to their magnetic nature (Mbachu et al. 2023). This is indispensable for understanding the structural and morphological features critical for IONP functionality in wastewater treatment applications. TEM offers high-resolution imaging, allowing the observation of IONP size, shape, dispersion, and crystalline structure at the nanoscale (El-Sheekh et al. 2021b). BET analysis measures the surface area and porosity by adsorbing and desorbing gas molecules and calculating the specific surface area and pore volume to understand nanoparticle reactivity and surface properties. The pH point zero charge (pHpzc) is crucial for characterizing iron oxide nanoparticles (IONPs), as it reveals their net surface charge and acidic or alkaline nature (Ha et al. 2021). This is essential for understanding adsorption processes, as it helps predict IONPs' interaction of IONPs with pollutants and optimize their effectiveness in various pH environments. The pHpzc also indicates surface modifications and functional groups that enhance adsorption properties, making it vital for designing effective IONPs for environmental and industrial applications (Ha et al. 2021).

Atomic Force Microscopy (AFM) is a cost-effective and versatile tool for characterizing iron oxide nanoparticles (IONPs). It provides high-resolution three-dimensional visualization, allowing for precise measurements of size, morphology, surface texture, and roughness. AFM operates in ambient air and liquid dispersions, is beneficial for biological studies, and offers a broad particle size range of 1 nm to 8 μm. Additionally, AFM requires less laboratory space and is simpler to operate than TEM/SEM, making it an ideal choice for nanoparticle characterization (Kumar et al. 2019).

Dynamic Light Scattering (DLS) is essential for characterizing the size and stability of iron oxide nanoparticles in solution. This study provides insights into how the molecular weight of grafted polymers affects the size and stability of nanoparticles. DLS allows for real-time monitoring of particle size changes, which is crucial for understanding nanoparticle behavior under various conditions, such as in water or physiological buffers (Boyer et al. 2009).

Methods for Analysis of Composition of Iron Oxide Nanocomposite: Energy Dispersive X-ray (EDX), X-ray Photoelectron Spectroscopy (XPS), and X-ray Diffraction (XRD) are pivotal techniques for the characterization of iron oxide nanoparticles (IONPs), each offering unique insights into their composition and structures. EDX provides rapid elemental analysis and mapping, which is essential for confirming the synthesis and surface modification of IONPs (Majumder et al. 2019). XPS facilitates detailed chemical-state surface analysis, quantitative elemental composition, and determination of metal oxidation states, revealing the presence of functional groups and the chemical environment of atoms on the nanoparticle surface (Majumder et al. 2019). XRD is crucial for characterizing the crystal structure, phase composition, and crystallite size, and identifying phases such as magnetite, maghemite, and hematite by analyzing diffraction patterns (Yadav et al. 2023). The Debye-Scherrer equation estimates the crystallite size, ensuring nanoparticle quality by detecting impurities and confirming the phase composition against standard reference patterns (Bhutto et al. 2023). Collectively, these techniques enhance our understanding of IONP properties and optimize their application in environmental remediation, biomedicine, and other fields (Rajendran et al. 2023).

Thermal Method for Characterization of Iron Oxide Nanocomposites: Thermogravimetric Analysis (TGA) is a critical technique for characterizing iron oxide nanoparticles (IONPs), offering valuable insights into their thermal stability and the presence of organic components. TGA measures the weight changes of nanomaterials as a function of temperature, enabling the detection of thermal decomposition processes and the identification of volatile or adsorbed substances (Kouhbanani et al. 2019). This method helps determine the extent of functionalization by assessing the weight losses related to the removal of moisture and decomposition of organic molecules, confirming the presence and stability of surface modifications. By providing a detailed thermal profile, TGA supports the verification of synthesis processes and the quality of functionalized nanomaterials, making it an essential tool in the development and application of IONPs in various fields (Sandhya and Kalaiselvam 2020).

Determination of the pH of Nanomaterials: PH point zero charge (pHpzc) is crucial for characterizing iron oxide nanoparticles (IONPs), revealing their net surface charge and acidic or alkaline nature (Ha et al. 2021). It is essential for understanding adsorption processes, as it helps predict IONPs' interaction with pollutants and optimize their effectiveness in various pH environments. The pHpzc also indicates surface modifications and functional groups that enhance adsorption properties, making it vital for designing effective IONPs for environmental and industrial applications (Ha et al. 2021). The pH of IONPs affects their stability, surface charge, reactivity, and interactions with other molecules or substances. pHzpc is an important factor in the absorption of heavy metals from wastewater (Mittal et al. 2023). pH-sensitive magnetic nanofibers are used for thermochemotherapy (Vo et al. 2024). The term "point of zero charge" (PZC) signifies the pH value at which the net surface charge resulting from the adsorption of the prospective ions H+ and OH- is zero. The PZC is essential for the purification of water, particularly for adsorption onto surfaces such as activated carbon. It affects the adsorption of organic pollutants, heavy metals, and other contaminants onto activated carbon surfaces (Nguyen et al. 2020). An examination was conducted to explore how the pH and SRHA (specific reactive surface area) impact the behavior of iron oxide nanoparticles. Both factors were found to be concentration-dependent, influencing the formation of open pores and aggregation (Baalousha et al. 2008).

ADVANTAGES OF IRON OXIDE NANOMATERIALS IN W&WT

The different advantages of iron oxide nanomaterials in W&WT are summarized as follows: (a) the green synthesis of iron oxide nanoparticles allows a greener approach for water purification (reducing chemical intervention in water treatment), (b) existing methods of water purification are effective, but some prevailing problems, such as packed column plugging, membrane fouling, and high-pressure treatment streams, can be prevented by the use of INOPS owing to their high degree of dispersion and versatile ability to get deposited/combined with numerous technologies for enhancement of filtration activities (Razali et al. 2023), and (c) the adsorption and catalytic conversion of pollutants into neutral components. Studies showed activities on polysaccharides and amino acids (Akhtar et al. 2024), Proteins (George & Kumar 2023), Polycyclic aromatic Hydrocarbon (Shanmuganathan et al. 2023), Pentachlorophenol (George et al. 2023) (d) IONP has shown high efficiency in the removal of inorganic substances like Zn (Ahmadi & Izanloo 2023), AsIII&AsIV (Priyadarshni et al. 2020, Torasso et al. 2021), Triclosan (Dhasan et al. 2023), (e) Another useful function that can be made possible (by exposing the nanoparticles to a magnetic field) is site-specific targeting and in-situ applications, (f) INOP provides a high surface area-to-volume ratio, which when considered with the high number of active sites, provides a high capacity and adsorption affinity for pollutants and high reaction kinetics (Priyadarshni et al. 2020, Ahmadi & Izanloo 2023), (g) Easy Recovery of nanoparticles can also be made, attributed to the magnetic properties of INOP (Powell et al. 2020) and (h) Nanoparticles can be used in a more synergistic approach enhancing a few properties like oil-water mixture separation (Khandan Barani et al. 2023) along with bacterial control due to the inherent properties of IONP.

SYNERGISTIC PROPERTIES OF IRON OXIDE NANOMATERIALS FOR W&WT

Currently, there are many reports on the synergistic activities of iron oxide nanomaterials in W&WT applications, which are summarized as follows: Alabresm et al. (2018) described the use of IONP with several bacterial strains, such as *Halomonas* sp., *Vibrio gazogenes*, and *Marinobacter hydrocarbonoclasticus*. These bacterial strains, along with nanoparticles coated with polyvinyl pyrrolidone, successfully removed lower- and higher-chain alkanes, with removal efficiencies of approximately 70% and 65%, respectively, within one hour of incubation. NPs with bacterial strains showed no immediate effects but had a significant increase in the removal of approximately 80-90% after 24-48 h. The study showed a synergistic effect of the combination of oil-degrading bacterial strains and surface-functionalized iron NPs. The system can effectively remove 100% of the oil within 48 h or less.

Shukla et al. (2021) provide a brief background of the metal oxide for synergistic remediation of the pharmaceutical-polluted wastewater by the effect of the photocatalyst and dopants simultaneously. This shows how the drawbacks of metal oxide nanoparticles can be overcome by doping, which enhances their photocatalytic rate. The literature also briefly describes metal oxides, including iron, copper, titanium, zinc, silver, tungsten, bismuth, and platinum.

Aboelfetoh et al. (2023) introduce a cost-effective and environmentally friendly approach for generating α-Fe_2O_3-CuO nanocatalyst. To create the α-Fe_2O_3-CuO nanocomposite, copper hexacyanoferrate was decomposed by mild-heating oxidation. XRD, SEM, FTIR, EDX, TEM, XPS, and VSM were used to verify the structure and surface morphology of the synthesized catalysts. In the presence of H_2O_2, α-Fe_2O_3-CuO acts as a catalyst to promote the thermal degradation of dyes such as direct violet 4, rhodamine B, and methylene blue. The catalytic activity of the nanocomposite increased owing to the synergistic action of Fe_2O_3 and CuO, surpassing that of the individual components. The incorporation of inorganic anions, such as chloride or nitrate, accelerated the breakdown process. However, sulfate and humic acid, especially in large amounts, delayed this process. The mechanism of H_2O_2 activation on α-Fe_2O_3-CuO was investigated. Chemical oxygen demand and total organic carbon measurements revealed that all colors were significantly mineralized. The capacity of this nanocomposite to effectively remove various colors renders it a viable solution for wastewater treatment.

Using a combination of ferrate (VI) and peroxymonosulfate, Feng et al. (2017) developed a method for efficiently breaking down four fluoroquinolone antibiotics in water. The combined method was more effective than the use of each oxidant alone. The study, which used LC-HRMS analysis, found that the mixture of oxidants caused the antibiotics to undergo hydroxylation, ring cleavage, and defluorination. These results highlight the potential of this method as a cutting-edge water treatment technique for removing organic contaminants. In another study, water decontamination occurred through the Fenton reaction, with CO and Fe ions showing a synergistic effect in the removal mechanism (Wang et al. 2022).

MECHANISM OF WATER REMEDIATION BY IONP-BASED NANOMATERIALS (IONPNMS)

Adsorption and desorption of metal and organic pollutants and photocatalysis of dyes are widely used mechanisms in research, along with a few new methods such as Fenton's oxidation and other electrochemical processes.

Adsorption and Desorption

As the name suggests, this mechanism is based on the capacity of surface adsorption of pollutants to remove them directly, which can then be desorbed to obtain iron oxide nanoparticles. Solvents are required for the desorption process, and they also have some major flaws, such as the loss of activity of iron oxide nanoparticles due to permanent adsorption on the surface. Some benefits can be stated as follows: a high surface area is present due to the smaller size, and the presence of the negatively charged hydroxyl group (OH^-)imparts a slight negative charge to the nanoparticle, making it effective in the removal of cationic pollutants, mainly heavy metals. Physisorption and chemisorption play major roles in pollutant binding, with physisorption providing a weaker bond than chemisorption. Another important point to be noted is that, as explained in the recovery of the nanoparticles, the cycles before efficiency loss must be maximized, which can be achieved by composite formation (Hussen Shadi et al. 2020).

Talbot et al. (2018) studied the absorption/desorption cycles of pH-sensitive magnetic alginate/-Fe_2O_3 NPs using methylene blue dye. Reusability is a crucial factor in evaluating NP performance. After exposure to the dye, the NPs were magnetically separated, washed with the solvent, and treated with nitric acid for desorption. Before the next cycle, the pH of the particles was raised to 7, and adsorption and desorption cycles were performed continuously. Nitric acid at pH 2 was used as a desorption agent. The observed desorption efficiency was 99%, and the adsorption capacity remained 100%, showing no signs of change even after 10 cycles. This study provides evidence for the potential application of alginate magnetic nanoparticles in water treatment. The composites of iron oxide NPS with organic and inorganic materials explored for the removal of metal ion pollutants are listed in Table 5; pollutant removal efficiency ranges from 96 % to 99 %. Micro boxes showed the removal of 97.30 % of Pb^{2+}, 96% of Cu^{2+}, 97.90% of Cd^{2+}, and 98.30% of Hg^{2+} contamination (Ravindranath et al. 2017). Multifunctional MIONPs (Fe_3O_4) modified with 2,3-dimercaptosuccinic acid/dopamine for heavy metal ion removal exhibited removal efficiencies of 49.46 $mg.g^{-1}$ for Cd^{2+} and 87.62 $mg.g^{-1}$ for Pb^{2+} (Lei et al. 2023).

Catalysis

Photocatalysis

The photocatalytic process operates under the assumption that the energy absorbed from light radiation is sufficient to equal or exceed the band gap energy of the semiconductor, demonstrating how the reactions occurring on a semiconductor material are photocatalytic (Topare et al. 2022). Electrons in the valence band of the semiconductor material are stimulated to move to the conduction band and leave holes in the valence band when the incident light energy exceeds the bandgap. The excitation produces electrons (e^-) in the conduction band and holes (hvb^+) in the valence band on the fs timescale. These are then recombined in the range of 10–100 ns after being trapped in 100 ps (shallow trap) to 10 ns (deep traps). The photo-induced electrons react with adsorbed oxygen or oxygen dissolved in water as part of the reduction process to generate $\bullet O^{2-}$. Subsequently, O^{2-} may combine with H^+ to generate a hydroperoxyl radical, which may then react to form H_2O_2 or hydrogen peroxide. H_2O_2 can react with electrons to form •OH. Meanwhile, the photo-induced holes

Table 5: Iron oxide nanocomposite and inorganic pollutant adsorption efficiency.

Nanoparticles	Composite designed with	Application for metal ion Pollutant	Pollution Removal Efficiency	References
FeO	-	Zn^{2+}	99%	(Ahmadi & Izanloo 2023)
FeO and CuO	Stabilized on biochar (rice husk)	As^{3+} As^{5+}	>95%	(Priyadarshni et al. 2020)
Fe_2O_3 and Al_2O_3	Microboxes	Hg^{2+} Pb^{2+} Cu^{2+} Cd^{2+}	98.30% 97.30% 96.00% 97.90%	(Ravindranath et al. 2017)
Fe_3O_4	Dopamine-Dimercaptosuccinic acid	Pb^{2+} Cu^{2+} Cd^{2+}	187.62 $mg.g^{-1}$ 63.01 $mg.g^{-1}$ 49.46 $mg.g^{-1}$	(Lei et al. 2023)

diffuse to the surface of TiO2 and produce •OH by reacting with the adsorbed water molecules in a neutral solution or the adsorbed hydroxyl group in an alkaline solution. •OH can degrade most organic compounds with second-order rate constants of 108-1010 $M^{-1} s^{-1}$. Reactive oxygen species and holes have the potential to facilitate oxidative processes, as explained by Khan et al. (2022).

Mansur et al. (2023) suggested that, in addition to their photocatalytic activity, biocompatible and ecologically harmless inorganic nanomaterials, including heavy metal-free semiconductors, have drawn increased attention since they meet the majority of sustainability criteria. Because they are non-toxic and environmentally benign, zinc-based compounds, such as oxides (ZnO) and chalcogenides (ZnS, ZnSe), are chosen over traditional highly toxic quantum dots (QDs, e.g., CdS, CdSe, CdTe, PbS, PbSe, etc.). This is the result of extensive research on binary semiconductor nanoparticles (II-VI NPs). In addition, Zn-based chalcogenide semiconductor nanoparticles, also known as quantum dots (QDs), experience the quantum confinement regime at minuscule sizes (< 5 nm), offering special optoelectronic characteristics for a variety of environmental and biological applications. They used carboxymethylcellulose (CMC) to stabilize magnetic iron oxide (MION, Fe_3O_4). To create hybrid multifunctional nanoplexes, MIONs were mixed with ZnS semiconductor quantum dots (ZnS QDs) that had been chemically biofunctionalized with epsilon-poly-l-lysine (εPL). The findings showed that strong cationic/anionic electrostatic interactions between the biomacromolecule capping ligands of the two nanoconjugates (polypeptide in ZnS@εPL and polysaccharide in Fe_3O_4@CMC) were responsible for the formation of the supramolecular colloidal nanoplexes. These nanosystems demonstrated the photocatalytic degradation of methylene blue (MB), a common water contaminant. MB was not the only dye utilized to test the selectivity of the photodegradation induced by the nanoplexes, methyl orange, Congo red, and rhodamine were also checked. The antibacterial activity of εPL against drug-resistant, Gram-positive and Gram-negative bacteria was confirmed. The mechanism of water remediation using IONPs is illustrated in Fig. 7.

Photo-Fenton Processes

Photo-Fenton reactions use Fenton reagents and irradiation to produce $HO^{\cdot}$ via the photo-reduction of ferric to ferrous ions, followed by hydrogen peroxide photolysis (Han et al. 2020). Photochemistry's contribution to this process is to generate energy by utilizing ultraviolet (UV) or visible light to increase the system's catalytic activity while simultaneously reducing the amount of catalyst used. Han et al. (2020) studied the efficiency of the photo-Fenton process in degrading pollutants such as tetracycline and oxytetracycline. After studying different methods, it was concluded that the UV light-assisted Fenton reaction ($UV/H_2O_2/Fe^{2+}$) was the most effective technique for removing pollutants from water. This conclusion was based on a comparison of the Fenton-like procedure with the H_2O_2, UV, and UV/H_2O_2 procedures. While incomplete antibiotic mineralization occurred, the resulting byproducts were identified and assessed for toxicity

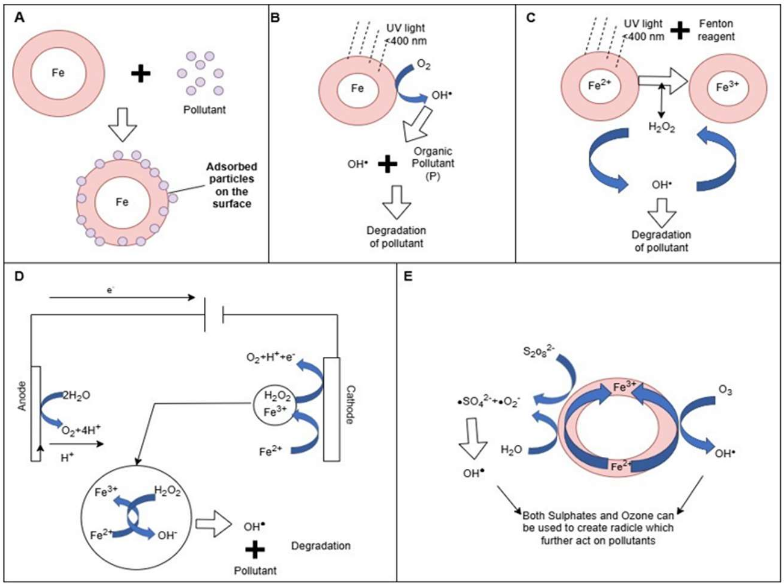

Fig. 7: Mechanisms of water remediation by IONP-based materials. A) Adsorption, B) Photocatalysis, C) Photo Fenton process, D) Electro Fenton process, E) Chemical oxidation process.

using a bacterial model. This is a critical concern, given the limited availability and energy-intensive production of UV light, which is commonly used in photo-Fenton processes. Visible-light-driven photoreactions offer a more cost-effective alternative (Liu et al. 2014).

Iron oxides, such as hematite, can absorb visible light due to their electronic band structure, however, their photocatalytic activity is limited because the e^-/h^+ couples recombine quickly (Santhosh et al. 2019b, Kumar et al. 2024). Photo-Fenton oxidation, which employs semiconductors with large bandgaps, such as TiO_2, is an effective charge-separation technique. Hassan et al. (2016) established a photocatalytic mechanism for methyl orange (MO) degradation using a Fe_2O_3/TiO_2 nanocomposite with visible light. Duca et al. (2023) examined the breakdown of toluene using IONP and H_2O_2 and found that benzaldehyde and bibenzyl were the predominant oxidation products. The results demonstrated that INOP could be reused without loss of efficiency, indicating the potential of heterogeneous photo-Fenton reactions to degrade aromatic contaminants such as toluene in water. This study demonstrates quicker reactions with Fe (II) and the benefits of employing IONP, which are less toxic and easy to reuse. The pH had a substantial impact on the processes, with optimum degradation occurring at approximately pH 3.0.

Electrochemical Processes

Electrochemical oxidation is one of the most extensively studied electricity-driven advanced oxidation processes (EAOPs) used for water remediation (Hodges et al. 2018). Pollutants can be converted into minerals by anodic oxidation, which transfers electrons directly to the electrode surface, or by indirect electro-oxidation, which creates strong oxidants (Buthiyappan et al. 2016, M'Arimi et al. 2020). Although this process has some advantages, such as versatility, ease of operation, and the ability to adapt to variations in flow rate and influent water composition, concerns about the formation of toxic byproducts, cost, and electrode performance issues can limit its application (Radjenovic & Sedlak 2015). Magnetic iron oxides facilitate rapid electron transfer, making them useful in electrocatalytic applications (Kudr et al. 2018, Topare et al. 2022). Researchers have developed composite electrodes containing magnetic particles to enhance these properties of the electrodes. Ribeiro et al. (2017) created a layered electrode using iron oxide nanoparticles and carbon nanotubes to detect salicylic acid, a drug metabolite and environmental pollutant.

The electro-Fenton technique, on the other hand, is one of the most widely used E-AOP. In this method, at least one ingredient for the Fenton reaction is generated in situ by utilizing electrons as reagents, where the following options might occur: hydrogen peroxide (H_2O_2) is produced at the negative electrode (cathode) and oxygen (O_2) at the positive electrode (anode). Iron ions (Fe^{2+}) can be added as a catalyst or generated from a dissolving iron anode. The final instance does not require the addition of chemicals, making the operation straightforward. The continuous in situ synthesis of H_2O_2 overcomes the issues associated with its transportation and storage. The disadvantage of this procedure is the production of iron hydroxide sludge, which requires proper disposal. Ferrous sludge emissions can be avoided by employing membranes (Muddemann et al. 2019).

Chemical Oxidation/Alternative Advanced Oxidation Processes

In search of alternatives to Fenton reactions, researchers have been exploring the activation of different oxidants to generate highly reactive radicals, leading to interest in species such as ozone and sulfates. Ozonation has been identified as a potential method for water cleanup. Pollutants can be degraded through two pathways: direct oxidation (molecular O_3) or complex chain reactions that produce HO radicals (Buthiyappan et al. 2016). Because the direct oxidation of O_3 is a selective technique, it produces partial mineralization at low rates. Furthermore, the limited solubility of ozone in aqueous solutions limits its practical application (Yu et al. 2020). Therefore, studies have used catalysts to increase ozone breakdown and ROS production. Chen & Wang (2019) employed a Fe_3O_4/Co_3O_4 composite for the catalytic ozonation of sulfamethoxazole (SMX), resulting in a 60% increase in pollutant mineralization. This finding was attributed to the increased surface area and reactive sites of the catalyst, which may have accelerated the interaction between O_3-SMX and free radical production. Various factors were studied, including pH, catalyst concentration, ozone, and contaminants, to determine which parameters had the best catalytic activity and how they impacted the reaction pathways.

Sulfate Radical-Based Advanced Oxidation Processes (AOPs)

This is a promising alternative to existing methods such as Fenton and ozonation. It uses persulfate (PS) and peroxymonosulfate (PMS) to generate sulfate radicals for water disinfection. Sulfate radicals offer several advantages, such as lower cost and higher stability than hydrogen peroxide and ozone, similar or higher oxidation power than hydroxyl radicals ($HO^{\bullet}$), a wide effective pH range (2-8), and eco-friendliness (Xiao et al. 2020). Iron oxide nanoparticles can activate peroxygen to form sulfate radicals, making them effective in this process. Research has shown that combining iron nanoparticles with PS or PMS enhances pollutant degradation compared to using them alone (Jegadeesan et al. 2019). The potential of IONP-based catalysts for ultrasound-assisted water treatment has been reported in the literature. These catalysts are a viable choice for effective and affordable water filtration because they are inexpensive, widely accessible, and safe (Zhang et al. 2018). Hassani et al. (2018) described the use of a heterogeneous Sono-Fenton method using Fe_3O_4 nanoparticles to remove the cationic dye violet 10. As predicted, the combination of both AOPs increased radical production under acidic conditions, leading to dye degradation. However, given that the dye was not fully mineralized, the authors emphasized the need to identify the by-products generated throughout the operation and their possible deleterious effects on the environment.

RECOVERY OF IRON OXIDE NANOMATERIALS

Iron oxide nanoparticles are valuable for water remediation because of their magnetic properties, which enable easy separation and reuse. However, current applications are limited to small-scale handheld magnet setups, hindering their use in large-scale or continuous water treatment (Leonel et al. 2021a). In recent years, there have been many advancements in the availability of statistically backed data on the in-line operation of magnetic devices. Powell et al. (2020) investigated an in-situ approach where the installation of a specially made magnetic nanoparticle recovery device (MagNERD) was under continuous flow. Its application was demonstrated for a smoother recovery of nanoparticles from water flow during water treatment. The device uses specific magnetic fingers to attract the nanoparticles and captures them inside stainless-steel wool wrapped around

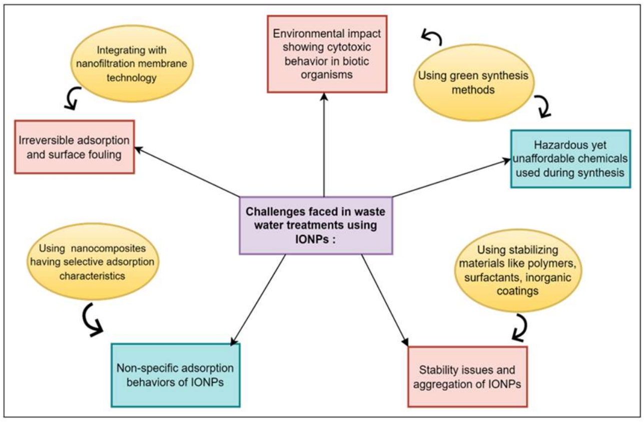

Fig. 8: Challenges in wastewater treatment using IONPs and their possible solutions (Bhuiyan et al. 2020, Leonel et al. 2021b, Epelle et al. 2022).

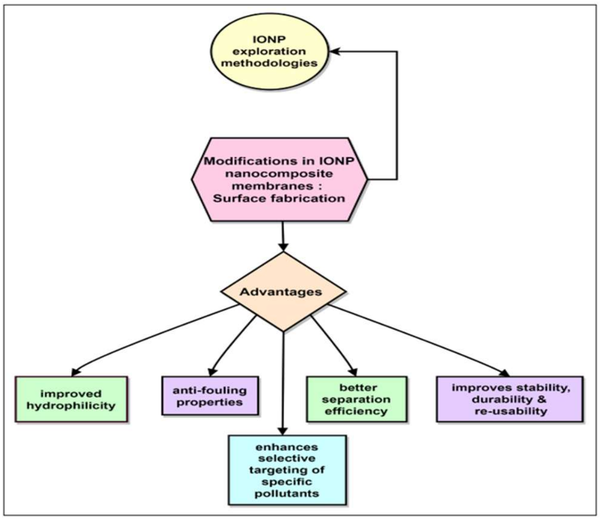

Fig. 9: Advantages of surface fabrication of IONP nanocomposite membranes.

the magnetic fingers. A unique approach was presented for separating nanoparticles after their use in effluent treatment. The recovery of the IONPs was attributed to their magnetic properties (Eldos et al. 2023).

In another recovery study, IONPs were recovered using acetone, ethanol, and distilled water, and these NPs retained their efficiency for approximately five cycles (Getahun et al. 2022). In a study, IONPs were immobilized on the surface of expanded graphite, where for the recovery of active surface, 0.1 M NaOH was found to have the utmost efficiency in the removal of the adsorbate and regenerating the adsorbent surface (Do et al. 2020). According to Shadi et al. (2020), recovery can also be facilitated with distilled water by varying the pH of the water. They also mentioned that the bond between the pollutant and the nanoparticle is relatively weak and can be broken simply by using a concentration of base or acid.

IONPS-BASED METHODOLOGIES FOR W&WT

Over the past few years, IONPs have been introduced for water and wastewater treatment (W&WT). The use of IONPs in such treatments has been the subject of much study and development to offer safe, long-lasting, and reasonably priced water treatment options while protecting the environment. Undoubtedly, certain limitations impede the practical implementation of IONPs, such as diverse obstacles. These challenges and possible solutions to the challenges are summarised in Fig. 8 (Tai et al. 2023, Bhuiyan et al. 2020, Leonel et al. 2021b, Epelle et al. 2022). Recently, iron oxide nanoparticles (Fe_3O_4) have sparked interest in modified nanocomposites by fabricating membranes. This modification is certainly aimed at its intrinsic properties that could improve membrane surface hydrophilicity, antifouling, etc., leading to better removal rates and durability of these membranes, as shown in Fig. 9.

IONP-Based Nano, Ultra, Reverse Osmosis (RO) Filtration Systems for W&WT

MIONPs embedded in nanofiltration (NF) membrane: Iron oxide (FeO) nanoparticles embedded in thin-film nanocomposite nanofiltration (NF) membrane for water treatment. Mixed matrix membranes demonstrate efficient nanofiltration mechanisms for dye removal. A special water flux enhancer called cobalt ferrite functionalized on bentonite ($CoFe_2O_4$@BT) was embedded in a polyethersulfone matrix. For Congo red, crystal violet, and humic acid, $CoFe_2O_4$@BT functions as a better flux enhancer and offers higher separation efficiencies of 95%, 94.69%, and 94.16%, respectively. Additionally, this type of NF membrane is better at preventing fouling, which lowers the membrane's ability to separate and purify substances. Consequently, it can retain its separation and purification capabilities for a longer duration. This NF membrane provides increased water flux and separation efficiency, preventing dyes from passing through and producing purified water (Maraddi et al. 2024). The proposed mechanism of dye removal by $CoFe_2O_4$@BT with improved anti-fouling properties for purified water production is shown in Fig. 10.

Iron Oxide-Functionalized Membranes for Toxic Metal Removal from Power Plant Scrubber Water: Iron-functionalized lab-scale membranes were created to reduce and adsorb selenium from scrubber water from coal-fired

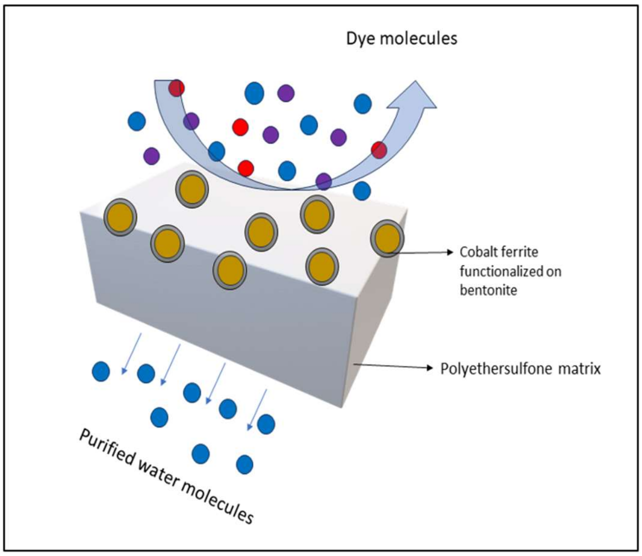

Fig. 10: Mechanism of dye removal by $CoFe_2O_4$@BT with improved anti-fouling properties.

power plants. Because iron-functionalized membranes prevent particle aggregation and dissolution, they are more effective than iron suspensions. Polyvinylidene fluoride (PVDF) membranes were coated with polyacrylic acid (PAA) to prepare lab- and full-scale membranes. This was followed by the ion exchange of ferrous ions and reduction to zero-valent iron nanoparticles. The highest ion exchange capacity was achieved at 20% PAA with highly responsive pH pores, as the percentage of PAA functionalization increased, while the water permeability of the membrane decreased (Gui et al. 2015).

An IONP-based MXene Composite Material for Ultra and RO Filtration: A mixed matrix membrane (MMM) was created using $ZnFe_2O_4$ and $Ti_3C_2T_x$ MXene composite, $ZnFe_2O_4@Ti_3C_2T_x$ MXene with polyether sulfone (PES). The composite improved the antifouling properties, pore structure, hydrophilicity, and surface polarity of MMMs. The ultrafiltration membranes (UFM) maintained their flux for five cycles of bovine serum albumin (BSA) solution/backwashing at approximately 350 $L \cdot m^{-2} \cdot h^{-1}$, demonstrating excellent stability. UFM exhibited the highest flow (324.56 $L \cdot m^{-2} \cdot h^{-1}$) and achieved high dye/salt separation (RCR = 97.3 and RNa_2SO_4 = 8%). This highlights the potential of PES MMMs containing $ZnFe_2O_4$@MXene for dye separation from high-salinity wastewater (Zhou et al. 2023). Sun et al. 2024 studied the process of creating a thin film by combining polyvinyl alcohol (PVA) with MXene@Fe_3O_4. This innovative combination enhanced the compaction of the coating materials and effectively prevented corrosive reactions on the metal surfaces.

An inorganic corrosion inhibitor, ferroferric oxide (Fe_3O_4), was electrostatically loaded onto Ti_3C_2 MXene nanofluids to obtain a hybrid material with improved corrosion resistance. In another study, an innovative 2D sandwich-layer structure was meticulously crafted using MXene-iron oxide (MXI) composites. These ultrafine nanocomposites have been discovered to be remarkably effective for sequestering phosphate in water purification processes. (Zhang et al. 2016). In one study, polyamide commercial reverse osmosis (RO) membranes were coated with iron nanoparticles (FeNPs) and graphene oxide (GO) to prevent biofouling. Tests showed that the GO-FeNP coating reduced biofilm thickness, total cell count, optical density, and total organic carbon compared to the uncoated membranes. Despite the reduced permeance, the coated membranes exhibited larger fluxes after fouling than the fouled uncoated membranes (Armendáriz-Ontiveros et al. 2019).

IONP Nanocomposites

Another highly efficient technique for treating wastewater is the preparation of IONP nanocomposites. One study suggested embedding IONP in a chitosan-lignocellulose fiber nanocomposite. The chemicals that were selectively targeted were negatively charged compounds, particularly acidic dyes (AR-18). This type of dye, along with (Acid Yellow: AY23, AY6), is excessively used in the textile, cosmetic, and food industries, where untreated water disposal poses a risk to aquatic animals and humans (Vargas et al. 2012). The separation occurs via a biosorption mechanism, as the adsorption of this model azo dye on chitosan depends on the temperature, pH, and ionic strength. The most suitable separation reaction conditions are low pH, where the protonation of amino groups occurs in chitosan, which increases electrostatic interactions with anions in AR-18 (Zhou et al. 2016). The nanocomposite's acidic dye removal rate remained at 99.68% through 10 consecutive cycles and could be easily recovered using magnetic fields and reused. Hemoglobin iron oxide (Hb/Fe3O4) composite is an additional example of another iron oxide composite used to remove various dyes from aqueous solutions, including indigo carmine, naphthol blue-black, erythrosine, tartrazine, Eriochrome black T, and bromophenol blue. Instead of adsorption, it demonstrated an electrostatic interaction mechanism. The adsorption demonstrated removal capacities over a range of 80–178 $mg.g^{-1}$, following a pseudo-second-order kinetic model and Langmuir isotherm equation. An additional benefit is that the composite can be separated from the aqueous solution using an external magnet (Essandoh & Garcia 2018). Various nanocomposites of iron oxide-based NPs are discussed in Section 3.

3D Printed Wastewater Filtration System for Targeted Arsenic Removal

Arsenic is an excessively found metal in groundwater that is used for drinking purposes by many people, especially in rural areas. To prevent ingestion of this highly toxic metal and to aim for cost-effective and large-scale treatment of groundwater bodies, an example involved a 3D printed water filtration system for arsenic metal removal was developed. The filters were developed by a 3D printing technique using AutoCAD 2016, stereolithography, and finally printed using a DeltaBot unit (Fig. 11). The heated nozzle melted and deposited polylactic acid (PLA) filament to prepare filters with channel widths varying from 0.8 to 4 mm. Further steps were then subjected to surface treatment using 10M HCl to enhance hydrophilicity and $Fe(OH)_3$ deposition via acid hydrolysis. Surface treatment was carried out using an iron (III) hydroxide solution, as shown in Fig. 11, with consequent drying (60°C for 12 h) to increase the binding of Fe(OH)3 brown color particles in the 3D PLA filter. Arsenic removal involves its adsorption on iron (III) oxide particles deposited on the filter. An isotherm study determined that

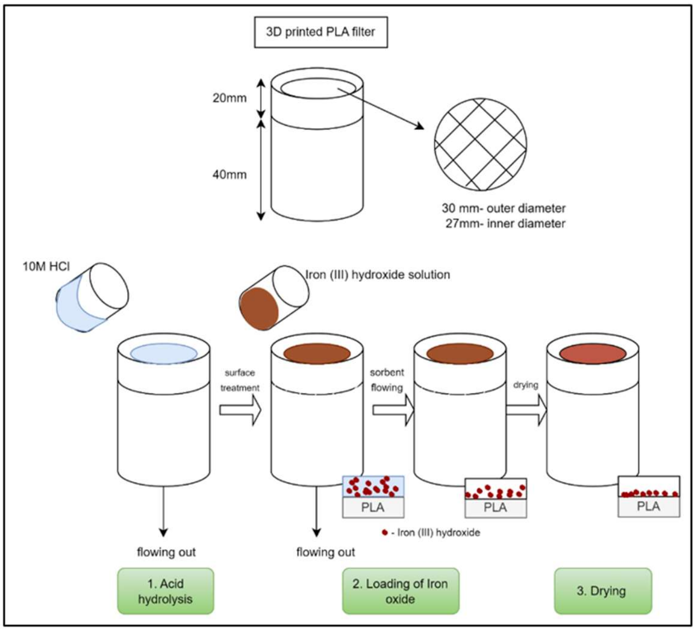

Fig. 11: Systematic steps to prepare a 3D printed PLA filter.

95 % As removal rates were achieved by a narrower channel (0.8–1 mm) filter, whereas rapid saturation and decreased As removal rates were observed in 1.8–4 mm filter channel sizes (Kim et al. 2020).

Use of Micro/Nanorobots for Water Remediation

The use of micro/nanomotors (MNMs) has opened exciting new possibilities for water remediation due to nanotechnology. MNMs are a novel class of IONP-based materials that can move autonomously, allowing them to interact with pollutants in water systems efficiently. These tiny motors transform energy into motion, enabling them to work together or independently to complete specific tasks. When it comes to environmental remediation, MNMs can be extremely helpful in treating water that has been contaminated by pathogens, organic compounds, toxic metals, and emerging pollutants. Owing to their ability to move and interact with their surroundings autonomously, MNMs can perform tasks depending on their parts and designs. MNMs can interact with pollutants through stacking interactions between aromatic rings, capturing them inside their pores, or adsorbing them through electrostatic attraction forces (El-Naggar et al. 2024).

By using their sensitive components for oxidant activation and energy conversion to trigger oxidation reactions, pollutants can also be broken down through oxidative processes. Additionally, MNMs are useful for detecting various types of pollutants because they can sense pollutants through colorimetric detection and fluorescence quenching techniques. MNMs can combat harmful microorganisms and are used for bacterial disinfection. Moreover, they can be used for disinfecting water, and various methods can effectively expand their use for disinfection to address additional harmful microorganisms (El-Naggar et al. 2024). IONP can be incorporated with self-fuelled motors, such as ZIF-67, to give micromotors Fe_3O_4/ZIF-67. Compared to regular Fe_3O_4 nanoparticles, the autonomous motion of the micromotors improved the degradation and removal of methylene blue dye.

CHOICE OF WATER REMEDIATION METHODS WITH IRON OXIDE NANOMATERIALS

Wastewater generated from various sources, such as agricultural practices, industrial practices, sewage, and wastewater sludge, is remediated through many mechanisms, such as adsorption, centrifugation, coagulation and flocculation, gravity settling, and filtration. Industrial wastewater is the main source of contamination and poses serious environmental hazards among all sources. Many recent advancements have focused on the remediation of water from industrial sources, such as chemical oxidation, biological treatments, membrane bioreactors, reverse osmosis, and adsorption techniques. Adsorption is the most frequently used technique for water remediation. Activated carbon has been used in the adsorption process using conventional techniques; however, the latest breakthrough in water treatment technologies is nanotechnology (Adegoke & Stenström 2019).

Magnetic nanoparticles and nanocomposites are the most efficient water remediation processes. Nanoparticles are a promising method for water remediation because of their easy synthesis, low cost, high surface-to-volume ratio, biocompatibility, catalytic activity, optical activity, and photoelectrical activity. The next section discusses the latest research on Iron Oxide Nanoparticles (IONPs) and offers information on the effective removal of various pollutants from industrial wastewater using this method.

METHODS FOR EVALUATION OF THE WATER TREATMENT EFFICIENCY OF NANOMATERIALS

General Methods

Total organic carbon (TOC): TOC is a carbon analysis tool that calculates the total amount of organic carbon in the effluent. To evaluate the wastewater's strength by calculating the amount of carbon-based chemicals present Is measured by oxidizing organic carbon directly or indirectly to CO_2 and water. Biochemical Oxygen Demand (BOD): Microorganisms continue to aerobically decompose waste material in the presence of oxygen until it is completely utilized. Chemical Oxygen Demand (COD): This parameter calculates the amount of oxygen required in water to oxidize both organic and inorganic materials. Oil and Grease (O&G): O&G components in wastewater are derived from hydrophobic plants and animals that are poorly soluble in water, making them less biodegradable by microbes. Removal of solids from water: The concentration of solid particles that can dissolve or suspend in wastewater was estimated using total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), total volatile solids (TVS), and total fixed solids (TFS). Nutrient removal efficiency: A measurement of the concentration of specific elements that can speed up eutrophication, the natural aging process of water bodies, such as phosphorus and nitrogen. Various elements were determined in the sample for the purpose of ammonia (NH), total Kjeldahl nitrogen (TKN), nitrogen typically as nitrate or nitrite (N-N), and total phosphorus (TP). The general tests used to evaluate the water treatment efficiency of nanomaterials are shown in Fig. 12.

Removal of Organic Pollutants

Dye Removal Efficiency from Effluents

Iron oxide nanoparticles are used to eliminate a variety of industrial wastewater generated from various sources. One of the most common wastes generated is dyes, which can have harmful effects on the environment, humans, and aquatic animals. Dyes can impede the photosynthetic activity of aquatic plants. The most efficient way to remove dye materials from effluents is by adsorption (Kalaiyan et al. 2025). Table 6 lists some applications of various modified IONPs for dye removal from wastewater.

Removal of Drugs and Pharmaceuticals from Effluents

Many residual pharmaceutical materials, intermediates, and other products are sometimes left untreated in effluents and discarded in water bodies, which can potentially harm the environment. This type of discharge can also occur via animal farms and human waste. Many antibiotics, anti-inflammatory drugs, anti-leprotic, anti-viral, contraceptives, lipids, beta-blockers, and anti-cancer agents can form toxic derivatives in post-chlorinated effluents (Adegoke & Stenström 2019). Excessive accumulation of antibiotics and antimicrobials has led to the development of antibiotic resistance in aquatic organisms and promoted changes in the aquatic microbiome. Chen 2015 discussed the anti-biotic

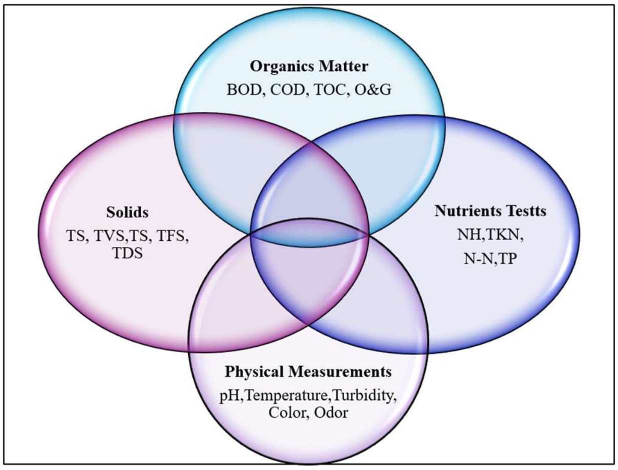

Fig. 12: General test used to evaluate the water treatment efficiency of nanomaterials.

Table 6: Applications of various modified IONPs for dye removal from wastewater.

Name of Adsorbent	Pollutant targeted	Removal efficiency	Adsorption isotherm fitting model	Reference
IONP embedded on chitosan-lignocellulose fiber nanocomposite	Acidic dyes [AR-18, AY23, AY6]	99.68%	Langmuir, Freundlich, Sips	(Zhou et al. 2016)
Fe_3O_4 and polyoxometalate hybrid nanocomposite	Methylene blue, Rhodamine B, Methyl Orange	97.84%, 91.22%,	Langmuir	(Li et al. 2019)
Fe_3O_4 modified with 3-glyciodoxypropyl trimethyoxysilane and glycine	Methylene blue, Orange I, Acid Red 10, Methyl Blue	90%	Langmuir	(Zhang et al. 2013)
Sodium dodecyl sulfate- modified Maghemite	Brilliant Cresyl Blue, Thionine, Janus Green B	93%	Langmuir	(Afkhami et al. 2010)
Carbon nanotubes and iron oxide-composed nanocomposite	Methylene blue, Neutral Red, Brilliant cresyl blue	99.16%, 98.33%, 98.8%	Freundlich	(Gong et al. 2009)
Fe_2O_3 cross-lined chitosan composite	Methyl Orange	98.25%	-	(Zhu et al. 2010)

ofloxacin having neurotoxicological effects and effects on marine fish biomes. The anti-inflammatory agent ibuprofen has been shown to inhibit the growth of aquatic plants. Pascoe (2003) showed that digoxin, a cardiac glycoside, depletes regeneration in aquatic animals.

In wastewater and water treatment applications, several methods, including photocatalysis, nanofiltration (NF), adsorption, and electrochemical oxidation, can be employed to further reduce or eliminate pharmaceutical pollutants from wastewater. Metal oxide nanoparticles can remove pharmaceutical contaminants present in quantities below the capacity of the most advanced processes. The treatment processes depend on the phase of the contaminant (organic/inorganic), size exclusion, charge repulsion, hydrophobicity, hydrophilicity, dipole movement, and hydrogen binding capacity (Adegoke & Stenström 2019). Fe_2O_3-NPs exhibit a wide range of antimicrobial properties (Dinesh et al. 2024). This is due to the high isoelectric point of 7, which results in a higher affinity to bind to the microbial cell wall. IONPs exhibit antimicrobial properties due to the oxidative stress generated by ROS. (Adegoke & Stenström 2019). Various pharmaceutical pollutants have been targeted by magnetic nanoparticles. Mahlaule-Glory et al. 2022discussed the preparation of Fe_3O_4 NPs by the green synthesis method from M. burkeana. It was found to have removal efficiencies of 99% for methylene blue and 60% for sulfisoxazole. Its action was more predominant towards gram-positive bacteria in water bodies.

Hussaini et al. (2023) prepared a magnetic nanocomposite using multi-walled carbon nanotubes and frankincense resin. They targeted amoxicillin, a broad-spectrum beta-lactam antibiotic that can cause antibiotic resistance in aquatic microbial biomes. The group performed adsorption studies using Langmuir and Freundlich isotherms, which showed that the nanocomposite was an excellent adsorbent for the remediation of amoxicillin-containing effluents, with a maximum adsorption efficiency of 322.2 $mg.g^{-1}$. The Langmuir isotherm explained the adsorption process more efficiently, revealing that the process was endothermic, spontaneous, and followed a physisorption process. The nanocomposites were effective in adsorbing amoxicillin for up to three cycles. Adel Naji & Tark Abd Ali (2023) developed a single-step method to prepare sand-coated magnetic nanoparticles and used the resulting nanocomposite to remove moxifloxacin and Cd^{2+} from the effluent. The coating method used green synthesis (vegetable peel extract) and co-precipitation. The study showed that the nanocomposite had removal capacities of 94% for moxifloxacin and 80% for Cd^{2+} from the effluents.

Removal of Inorganic Pollutants

The rapid increase in population has increased the demand for materials for livelihood. This demand has led to increased agricultural activities and other industrial manufacturing, which may result in inappropriate waste management (Topare et al. 2023). Improper waste disposal results in untreated water, waste, and pollutants being released into waterways, soil, and air. Lead (Pb), mercury (Hg), silver (Ag), tin (Sn), platinum (Pt), gold (Au), copper (Ni), arsenic (As), molybdenum (Mo), nickel (Ni), vanadium (V), manganese (Mn), cobalt (Co), copper (Cu), zinc (Zn), and arsenic (As) are among the most prevalent inorganic pollutants. Roy et al. 2021 performed a review on nanomaterials for the remediation of environmental pollutants that are dumped in water bodies, causing the risk of ingestion and further complications for humans and aquatic life. The applications of modified iron oxide NPs for the removal of inorganic pollutants are presented in Table 7.

Table 7: Applications of modified IONPs for dye removal from wastewater.

Adsorbent	Targeted pollutant	Mechanism	Reference
Iron oxide functionalized polyvinylidene fluoride (PVDF) membranes coated with 20% PAA	Selenium (Se), As, Ni, Hg, NO_3-	Nanofiltration	(Gui et al. 2015)
IONPs prepared from the steel pickling process	Pb^{2+}, Cr^{6+}	Adsorption	(Mwebembezi et al. 2024)
IONPs prepared from seed extract of Pheonix dactylifera	Cr^{6+}	Adsorption	(Kumar Chelike et al. 2024)
Zero valent IONPs derived from leaf extract of Green mulberry and Oak	As^{3+}	Adsorption	(Poguberović et al. 2016)

Antimicrobial Efficiency of IONP-Based Materials

Minimum Inhibition Concentration (MIC)

To determine the lowest inhibitory concentration, nanoparticle samples (Fe-NPs, Fe–Ag NPs, and Fe–Ag-CS NPs) that demonstrated antimicrobial activity during antibacterial screening were subjected to additional testing. Microbroth dilution studies were performed using 96-well microtiter plates to assess MICs. The MICs of the NPs against the studied bacteria were calculated using the microdilution broth technique, as detailed by the NCCLS. At 37 °C, the incubation period was continued for 24 h. After the incubation period, each well was treated with 5 µL of Resazurin sodium salt dye solution (R7017 Sigma-Aldrich). The absence of microbial growth in the microwells (column 11) containing only media confirmed that plate contamination did not occur during dish preparation. In contrast, additional columns 1–10 display the serial dilution of the NPs with the medium, ranging from 1 $mg.mL^{-1}$ to 0.0019 $mg.mL^{-1}$. This method addresses significant color and solubility issues that could impede growth evaluations for various medications and helps provide reliable MIC values. (Faiz Jaha et al. 2024).

Estimation of Minimal Bactericidal Concentration (MBC)

The least bactericidal concentration (MBC) is the lowest concentration of samples treated with Fe-NPs, Fe–Ag NPs, and Fe–Ag-CS NPs at which the inoculated bacteria were killed. Next, 10 µL of the media from the microplate containing the MIC was spread out and incubated for 24 h at 37°C without showing any signs of bacterial growth. Subsequently, the nutrient agar plates were re-inoculated. The first well with colony counts of fewer than five, which was considered detrimental to growth, was the MBC (Faiz Jaha et al. 2024).

Disk Diffusion Method

Mueller Hinton Agar (MHA) was used as the growth medium. MHA was supplemented with 106 colony-forming units per milliliter ($CFU.mL^{-1}$) of several bacterial strains. Then, Fe-NPs, Fe-Ag NPs, and Fe-Ag-CS NPs were impregnated into 7-mm paper filter discs at a concentration of 1 $mg.mL^{-1}$. The agar was then covered with the discs. Sterile distilled water (SDW) was used as the negative control. The nanoparticles were allowed to diffuse into the medium at room temperature for 30 min. The plates were then incubated for 24 h at 37°C. The average and standard deviation (SD) of three different trials were calculated to determine the inhibition zone. (Faiz Jaha et al. 2024).

Biofilm Formation Measurement

96-well polystyrene plates were used to evaluate biofilm formation by various bacterial strains. Overnight bacterial cultures were standardized to an OD60 nm of 0.5 in LB medium and subsequently co-cultured for 24 h at 37°C in the presence of varying concentrations (100, 50, 25, 12.5, 6.25, 3.12, and 0 $\mu g.mL^{-1}$) of green-produced Fe_3O_4 NPs. A control group without MNPs was also included in the study. Bacterial proliferation was monitored by measuring the absorbance at OD600 nm using UV-Vis spectroscopy. Planktonic microorganisms were removed by repeated washing with water. Biofilms were stained with crystal violet (0.1%, v/v) for 30 min at 25°C, followed by washing and blotting. The extracted crystal violet was quantified at OD570 nm to assess the total biofilm formation (Alavi and Karimi 2019). To ensure experimental reproducibility and statistical significance, all experiments were conducted in triplicate, and the results are reported as mean values ± standard deviations (SD) of three independent cultures. Tukey's test ($p \leq 0.05$) was used to determine statistically significant inhibition of biofilm formation.

SAFETY OF IRON OXIDE NANOMATERIALS

A range of techniques, such as in vitro, in vivo, and ecotoxicological assays, are commonly used to evaluate iron oxide nanoparticle properties. Fig.13 provides a summary of these approaches, with detailed explanations in the preceding sections of this review, highlighting their role in evaluating nanoparticle toxicity.

Biological Impact and Safety Risks of Engineered Iron Oxide Nanoparticles

Iron oxide nanoparticles (IONPs) are increasingly prevalent in the environment and are found in various forms, such as particulates from air pollution and volcanic eruptions. Their presence in emissions from industries, traffic, and synthetic nano-wastes has been proven to have a significant impact on the environment and ecosystems. As the use of IONPs increases, so does their exposure to water, air, and soil, necessitating a thorough evaluation of their nanoecotoxicity in natural and experimental settings (Kalaiarasu et al. 2025). Understanding the safety and environmental implications of IONPs is crucial because of their potential interactions with biological systems and the environment. Concerns regarding the interactions of synthetic iron oxide-based nanomaterials with the environment and their possible effects on aquatic ecosystems have been raised due to the increasing use of these materials. Although often considered non-toxic, these materials can change, such as agglomeration, adsorption, dissolution, and redox reactions, which alter their properties and toxicity.

Factors such as pH, surface coatings, ionic strength, and natural organic matter (NOM) significantly affect the behavior of nanoparticles in water (Leonel et al. 2021c). For instance, pH affects the zeta potential (ZP) of NPs, influencing their stability and tendency to agglomerate. Surface coatings and NOM can either stabilize or destabilize NPs, depending on the environmental conditions. For example, uncoated Superparamagnetic Iron Oxide Nanoparticles (SPIONs) have low dispersibility, leading to high agglomeration rates, and appropriate coatings can stabilize the nanoparticles and prevent the release of toxic ions. Common SPION coatings include biological molecules, polyethylene glycol (PEG), dextran, and polyethylene oxide (PEO). Although PEG coatings reduce immunogenicity, PEG-SPIONs have been proven to be more toxic than bare dextran SPIONs. Comparing bare SPIONs with thin silica-coated SPIONs on A549 and HeLa cell lines showed that coated SPIONs reduce oxidative stress and lower iron ion release; however, dextran-coated SPIONs can induce cell death similarly to uncoated SPIONs (Leonel et al. 2021b). When iron oxide NPs enter the environment, they interact with living organisms, influencing oxidation- and reduction-related chemical transformations. These interactions can result in the formation of reactive oxygen species (ROS), metal ion release, and cellular uptake, which may have cytotoxic effects. The exact mechanisms underlying these effects are complex and require further investigation (Leonel et al. 2021c). Different nanotoxicity evaluation assay methods used for iron-based nanomaterials are presented in Fig. 13.

Assessment of *In Vitro* Nanotoxicity

The in vitro assessment of iron oxide nanoparticles (SPIONs) is critical for evaluating their uptake, biomedical fate, and cytotoxic effects. Reactive oxygen species (ROS) generation and cell viability are critical parameters for assessing cellular responses to various treatments, including nanoparticles and stress-inducing agents. These studies highlight that the toxicity and cellular response to SPIONs are influenced by factors such as nanoparticle size, surface modifications, dose, and cell type. Various cytotoxicity assays on different cell lines revealed that the interaction and uptake of SPIONs depend significantly on the surface charge, with positively charged SPIONs generally exhibiting higher toxicity owing to greater cellular uptake. Furthermore, amine, carboxyl, and hydroxyl functional groups on the nanoparticle surface can alter their toxicity, with hydroxyl-rich SPIONs showing lower toxicity. These in vitro assessments are vital for understanding the cellular fate of SPIONs,

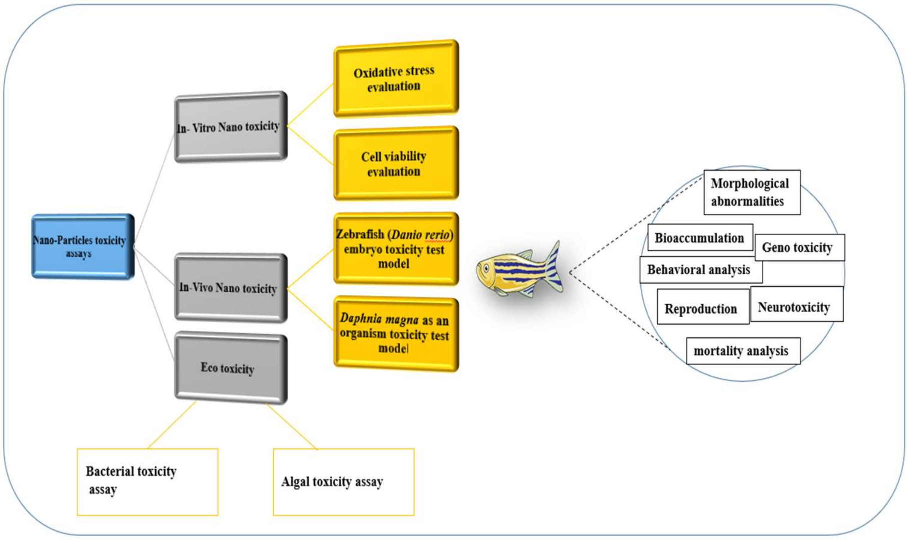

Fig. 13: Different nanotoxicity evaluation assay methods used for iron-based nanomaterials (Leonel et al. 2021c).

including their internalization, interaction with cellular organelles, and potential to induce reactive oxygen species (ROS), leading to cellular damage (Vakili-Ghartavol et al. 2020b).

Oxidative Stress Evaluation

Iron oxide nanoparticles (IONPs) enhance reactive oxygen species (ROS) production, leading to cytotoxicity and oxidative damage. This can be detected by measuring ROS levels, assessing oxidative damage to proteins, lipids, and DNA, and evaluating antioxidant status. IONPs induced oxidative stress in rat lymphocytes through ROS and glutathione depletion, causing dose-dependent cytotoxicity and reduced catalase activity. Thymoquinone, a natural antioxidant, mitigates these harmful effects (Leonel et al. 2021b). The generation of ROS can be evaluated using multiple approaches. Gaharwar et al. (2017) and Ansari et al. (2019) have demonstrated the measurement of enzymatic activity involving catalase (CAT), glutathione (GSH), and superoxide dismutase (SOD), which are crucial antioxidant enzymes. Lipid peroxidation, another indicator of oxidative stress, was assessed as described by Ansari et al. (2019). Additionally, changes in the mitochondrial membrane potential, a marker of mitochondrial health and function, were examined (Gaharwar et al. 2017). The use of DCF fluorescence intensity to measure intracellular ROS levels was detailed by (Leareng et al. 2020) and the MTT assay, which measures cellular metabolic activity, was utilized by Carvalho et al. (2019) and Ansari et al. (2019). These methodologies collectively provide a comprehensive evaluation of ROS generation under experimental conditions.

Cell Viability Evaluation

Colorimetric assays are often used to assess the potential toxicity of iron oxide nanoparticles (IONPs). Techniques such as the MTT assay measure mitochondrial activity by quantifying formazan crystals formed by viable cells, whereas trypan blue (TB) and lactate dehydrogenase (LDH) assays assess membrane integrity and cell damage. Although these methods provide valuable insights into nanoparticle-induced cytotoxicity, direct *comparisons across studies are challenging because of variations in experimental conditions, nanoparticle properties, and cell types (Deda et al. 2017, Leonel et al. 2021b).*

Assessment of *In Vivo* Nanotoxicity

Animal models are used in in vivo assessments of iron oxide nanoparticles (IONPs) to determine their toxicity and possible health impacts. Typically, adult rats are exposed to IONPs through methods such as intratracheal instillation. The rats were divided into different groups, including untreated controls and various dose groups, and body and organ weights were monitored throughout the study. Histopathological examinations, including organ weight measurements and tissue staining, were conducted to detect any abnormalities or damage. Intra-tracheal instillation of low-dose (LD) and high-dose (HD) iron oxide nanoparticles (IONPs) caused reduced body weight gain and significant lung weight decrease in rats, with inflammation and mild pulmonary fibrosis, especially in the HD group. Liver and kidney weights initially decreased but normalized over time, emphasizing the potential pulmonary toxicity of IONPs (Szalay et al. 2012). These studies helped identify significant changes in body weight, organ weight, and tissue pathology associated with nanoparticle exposure. Such evaluations are crucial for understanding the environmental risks and potential health impacts of IONPs (Szalay et al. 2012, Leonel et al. 2021b).

Zebrafish (Danio rerio) Embryo Toxicity Test Model

Zebrafish (*Danio rerio*) are highly suitable for evaluating iron oxide nanoparticle (IONP) toxicity because of their rapid development, large egg production, and genetic similarity to humans. According to studies, zebrafish are superior to mammalian models in terms of cost, time efficiency, and sensitivity. This model has been extensively used for nanotoxicity assessment, including investigations into the effects of maghemite nanoparticles. Zebrafish embryos exposed to various concentrations of IONPs showed concentration-dependent mortality, indicating that both static and semi-static exposure conditions influence nanotoxicity. Despite high mortality rates at higher concentrations, IONPs did not affect the hatching rate, highlighting the need for specific guidelines for nanoparticle testing (Pereira et al. 2020a). Morphological abnormalities in zebrafish have been used as indicators of developmental toxicity (Chakraborty et al. 2022). Bioaccumulation and biodistribution studies, which track the internal distribution and accumulation of nanoparticles, were described in detail by Haque and Ward (2018). Behavioral analyses, including swimming kinetics and spatial recognition, provide insights into the neurobehavioral effects of nanoparticles and were covered by both Haque and Ward (2018) and Chakraborty et al. (2022). Reproduction and mortality analyses provide critical data on reproductive toxicity and overall survival impact, as highlighted in studies by Haque and Ward (2018) and Chakraborty et al. (2022). Additionally, genotoxicity and neurotoxicity evaluations, such as those conducted by Pereira et al. (2020), and assessments of endocrine disruption, as reported by Pereira et al. (2020b) and Chakraborty et al. (2022), provide further insight into the toxicological effects at the genetic and hormonal levels.

Daphnia magna Organism Toxicity Test Model

Daphnia magna, a tiny planktonic crustacean, serves as a crucial model for ecotoxicological research because of its regular parthenogenetic life cycle and the simplicity of its cultivation and handling. Research has shown that different iron oxide nanoparticles, such as magnetite and hematite, lead to distinct toxic outcomes owing to variations in their physicochemical properties. For example, Fe▯O▯ nanoparticles demonstrate higher dissolution and oxidation rates, causing significant metabolic disturbances within the organism. Additionally, the surface reactivity of nanoparticles can influence their toxicity, with effects linked to specific biointeractions with reactive surfaces. These findings highlight the critical relevance of nanoparticle composition and surface chemistry in assessing ecotoxicological risks in aquatic systems (Leonel et al. 2021b). Kwon et al. (2014) conducted bioaccumulation and biodistribution studies using Daphnia magna to understand the internal concentrations of nanoparticles. Morphological changes, which can signal physical deformities or stress responses, were documented by Valdiglesias et al. (2016). Physiological changes, including swimming motility, vertical migration, and feeding rates, were examined by Prajitha et al. (2019) to assess their impact on vital physiological functions. Reproduction and mortality analyses, which are essential for understanding the long-term effects on population dynamics, were also reported by Valdiglesias et al. (2016). These methods collectively offer a robust framework for assessing the in-vivo toxicity of iron oxide nanoparticles in aquatic models

Assessment of Ecotoxicity

The use of iron oxide nanoparticles (IONPs) in water remediation has attracted considerable interest; however, their potential ecotoxicity poses substantial risks to aquatic ecosystems. These manufactured nanoparticles can be introduced into freshwater and marine environments. lead to adverse effects across various trophic levels owing to processes such as bioconcentration and biomagnification. Once in the environment, IONPs can accumulate in organisms, potentially disrupting physiological processes and leading to toxicological effects. The persistence of these nanoparticles in aquatic systems can result in their gradual accumulation in higher trophic levels, amplifying their impact on ecosystems. Consequently, assessing the ecotoxicity of iron oxide nanoparticles is imperative to mitigate their environmental footprint and safeguard water resources. Understanding the interactions of IONPs with aquatic organisms and the broader ecosystem is essential for developing effective strategies to minimize their adverse effects and ensure their sustainable use (Leonel et al. 2021b).

Bacterial Toxicity Assay

Bacteria are essential in aquatic ecosystems and are used to quickly screen for water contaminants because of their rapid response to environmental changes. Bacterial assays assess toxicity by measuring changes in growth or cell viability, often through absorbance analysis or agar plate inhibition zone measurements. Studies have shown that metal oxide nanoparticles can inhibit bacterial growth, and this effect depends on nanoparticle-bacteria interactions (Jadhav et al. 2023). For example, chitosan-coated magnetite nanoparticles were more toxic to bacteria because the positive charge of chitosan attracted the nanoparticles more strongly to the bacterial surfaces, leading to increased bacterial death (Leonel et al. 2021b). The test used for the evaluation of iron-based nanomaterials in this regard was discussed in Section 12.4 as the antimicrobial efficiency of IONP-based materials.

Algal Toxicity Assay

Algae, as primary producers in aquatic ecosystems, play a crucial role in assessing water quality because of their sensitivity to pollutants. Algal assays, which measure parameters such as fluorescence and cell counting, are effective for evaluating the impact of iron-based nanoparticles on growth. Research has shown that factors such as nanoparticle size, crystal phase, and oxidation state significantly affect algal toxicity through mechanisms such as oxidative stress and interactions with nanoparticles. Nanosized iron oxides, in particular, exhibit greater toxicity than their bulk forms because of increased internalization and oxidative stress (Leonel et al. 2021b). Additionally, Gambardella et al. 2014 found that metal oxide nanoparticles, including Fe_3O_4, caused significant toxic effects when marine microalgae (Cricosphaera elongata) contaminated with 5 mg L^{-1} of various NPs were fed to sea urchin larvae (Paracentrotus lividus). The study observed reduced larval survival and abnormal development, indicating that metal oxide NPs can adversely affect aquatic organisms and potentially enter the food chain of higher organisms.

Factors Influencing the Toxicity of Nanoparticles

Size and shape: When the surface area increases and the particle size decreases, the reactivity of molecules increases, leading to unsatisfied bonding and faster diffusion in the gastrointestinal tract. Smaller particles can induce necrosis and apoptosis. Nanoparticles can easily enter the bloodstream and reach mucosal and lymphatic tissues (Suh et al. 2009). Sukhanova et al. 2018 show that smaller nanoparticles can easily cross cell barriers. Particles smaller than 25 nm can cross membranes via pinocytosis/endocytosis (Zhang et al. 2015, Sahay et al. 2010, Cypriyana et al. 2021).

Surface chemistry: Different metals have different surface chemistries, which greatly influence the toxicity of their nanoparticles. For instance, the surface coating and charge of superparamagnetic iron oxide nanoparticles (SPIONs) affect their interactions with biological systems. (Shagholani et al. 2018). Coatings such as polyethylene glycol (PEG), dextran, and polyethylene oxide (PEO) are commonly used to stabilize SPIONs (Sadeghiani et al. 2005, Lacava, 2001, Mojica et al. 2014). However, different coatings can lead to varying toxic responses in the body. It is important to conduct further studies to better understand the mechanisms underlying the toxicity of SPIONs (Berry et al. 2003, Cypriyana et al. 2021).

HANDLING AND DISPOSAL OF IRON OXIDE NANOMATERIALS

The Nanotechnology Safety and Health Program of the Office of Research Services Division of Occupational Health of the National Institutes of Health provides guidelines for mitigating occupational exposure risk and safeguarding oneself using personal protective equipment (PPE), gloves, respirators, dust masks, and surgical masks. Guidelines and best practices for the proper handling of nanomaterials in research laboratories and industries are provided by nanoscience and technology. In that study, it was stated that in the hazard area designated by the relevant authorities, milligram ranges of nanomaterials should be disposed of in sealed containers that are adequately labeled and removed by following the usual method (Centre for Knowledge Management of Nanoscience and Technology 2016). Different methods can be used for the disposal of nanomaterials.

W&WT APPLICATIONS OF IONP-BASED NANOMATERIALS

Various specialized applications of IONP-based nanomaterials for W&TT were discussed in previous sections. Various synergistic applications of the materials, such as synergistic oil removal/recovery with microbial species, the synergistic photocatalytic effect of other metal-doped IONPs, synergistic thermal degradation of dyes by α-Fe_2O_3-CuO NC, and the synergistic effect of ferrate (VI) within the degradation of antibiotic pollutants, have been discussed. Specific mechanism-based applications of water remediation by IONP-based nanomaterials, such as adsorption/desorption, photocatalysis, photo-Fenton processes, electrochemical processes, chemical oxidation, alternative advanced oxidation processes, and sulfate radical-based advanced oxidation processes (AOPs), are discussed. IONP-based methodologies for W&WT, such as nano, ultra, reverse osmosis (RO) filtration systems, MXene composite material for ultra and RO filtration, iron oxide functionalized membranes for toxic metal removal from power plant scrubber water, 3D printed filtration system, and micro/nanorobots for water remediation, have been discussed. A few applications based on methods for evaluating the water treatment efficiency of nanomaterials have also been discussed. Nanotechnology enables the modification of materials at the nanoscale to achieve specific properties and functions. Iron oxide nanoparticles are widely used in wastewater treatment because of their low cost, high surface area, strong adsorption capacity, and ability to be separated using external magnetic fields. They are effective for pollution control, sensing and detection, and treatment and cleanup. A few additional applications of IONP-based nanomaterials are also discussed.

IONP-Based Removal of Ammonia from Fish Culture Tanks and Microplastic

As ammonia buildup in fish culture tanks can be harmful to aquatic ecosystems, it is a serious concern. Saharan et al. (2014) suggested that traditional techniques for removing ammonia, such as chemical treatment and biological filtration, can be resource-intensive and may not always work (Tang et al. 2022, Hao et al. 2024). Iron oxide nanoparticles, which have been demonstrated to successfully remove a variety of pollutants, including ammonia, from aqueous environments, are promising substitutes (Saharan et al. 2014). Although research on the application of iron oxide nanoparticles for ammonia removal in fish culture tanks is still in its infancy, previous investigations have produced encouraging findings (Mohamed et al. 2023).

Aquaculture is an emerging field in food production. Maintaining water quality is crucial in this rapidly expanding field to ensure sustainable fish production. Barik et al. (2023) discussed the synthesis of Fe nanoparticles using *Bacillus megaterium* collected from soil samples. The bacterial sample was isolated and identified, and its 16S rRNA gene PCR-amplified sequences confirmed the identification of the bacteria. Further, it was subjected to resuspension in FeCl3, which resulted in the formation of Fe nanoparticles. The synthesized nanoparticles were characterized using UV-Vis spectroscopy, FTIR spectroscopy, XRD, DLS-zeta potential, and TEM. Their efficacy in removing ammonia was evaluated under ex-situ and in-situ conditions from common carp and Cyprinus carpio culture tanks. Ammonia was removed from the tanks using a chemisorption mechanism. Despite recent developments in this area, the effectiveness of nanoparticles in removing ammonia from fish culture tanks remains unknown.

Various industries have increased their use and demand for plastics because of the versatility, durability, resistance, and cost-effectiveness of plastic products. Plastics are essential components of packaging, automotive parts, electronics, and medical devices. Plastics are supported by advanced manufacturing techniques that allow them to be utilized according to the desired properties required in the industrial sector. E-commerce is growing, and consumer goods production has exacerbated consumption.

However, this increase has raised environmental concerns, encouraging research into more sustainable solutions (Heo et al. 2022a). Because of their microscopic size, microplastics can evade most filtration systems, making their removal from water extremely challenging. Heo et al. 2022b assessed Magnetic iron oxide (Fe_3O_4) nanoparticles as viable options for the adsorptive removal of microplastics. Their study focused on the possibility of using magnetic Fe_3O_4 nanoparticles to filter microplastics from water through adsorption. They used polystyrene (PS) microparticles to model the microplastic behavior. The researchers investigated the isothermal adsorptive properties and process kinetics of polystyrene microparticles on Fe_3O_4 nanoparticles. They also conducted adsorptive tests for distinct groups of polystyrene microparticles with variable average diameters to investigate the adsorption efficacy of Fe_3O_4 nanoparticles. Fe_3O_4 and polystyrene adsorption involves both hydrophobic and electrostatic dynamics.

Oil Field Application

Enhanced Oil Recovery (EOR): IONPs have gained attention in enhanced oil recovery (EOR) due to their unique properties. The properties of IONP-based nanomaterials are very useful, and their application in oil recovery was reviewed, and their effectiveness was compared with that of other NPs. Role of IONPs in surface coatings, challenges in reservoir applications, and their potential solutions. Surface treatment has shown higher potential applications to enhance stability, transport, and minimize rock adsorption for increased oil recovery. Thus, IONP-based nanomaterials are economical, ecologically benign, and have potential for oil-field applications. (Yakasai et al. 2022). Oil Droplet Removal: IONPs are used to remove oil droplets from water in oilfields through coagulation and flocculation procedures (Jabbar et al. 2022).

Coagulation and Turbidity Removal

Almarasy et al. (2019) investigated and synthesized hematite iron NPs (α-Fe_2O_3) removal of turbidity. The efficacy of the NPs was compared with that of alum. The study revealed a 93.8% turbidity removal by α-Fe_2O_3 NPs. In another study on the use of magnetic nanoparticles in water treatment, the findings highlighted the benefits of integrating magnetic nanoparticles into the coagulation/flocculation process. The findings revealed various benefits of IONP materials for coagulant/flocculant-based W&WT. Better coagulation/flocculation by IONPs was achieved due to the high charge density (Fe^{2+} and Fe^{3+}) in a shorter time. The recovery of magnetic NPs and coagulant/flocculant can be achieved using an external magnetic field, providing a scale of economy (Mohamed Noor et al. 2022). Iron-loaded zeolites and ozonation (O_3/Fe-ZA) is a new household-level treatment that removes As and bacteria from tap water using a combination of iron-loaded zeolites and an ozonation process (Ikhlaq et al. 2021).

FUTURE PROSPECTS

Although there have been significant advancements, magnetic nanoparticles are still mostly used in laboratories, with only a few marketed technologies. The use of magnetic nanoscavengers for wastewater treatment poses a significant challenge owing to concerns regarding human health and environmental hazards. There have been reports of toxicity associated with the use of these nanoparticles, which may be the reason they are not widely accepted as a treatment for wastewater. The practical use of enhanced co-precipitation and hydrothermal procedures presents challenges for large-scale synthesis. Green synthesis is an essential goal for establishing the manufacture of sustainable and economical adsorbents. Furthermore, to facilitate their application in water treatment technologies, scalable and reasonably priced production procedures are being developed. Fe_3O_4 adsorbents must be functionalized with surface agents to increase their adsorption capacity, stability, efficiency, and selectivity.

Recent advancements in the application of iron oxide nanoparticles (IONPs) for wastewater treatment have illuminated the potential challenges and avenues for future research in this field. This study also identified potential obstacles and solutions related to the long-term sustainability and environmental impact of such water purification systems. Research has demonstrated the great potential of ferrofluids, magnetic ionic liquids, magnetic microrobots, and nanorobots for water remediation. However, to meet commercial demands, the translation of this technology into practical applications would require the collaborative efforts of scientists from diverse fields, such as engineering, physics, chemistry, and biology.

Future studies should focus on the selective removal of certain pollutants from industrial effluents using low-cost and efficient technologies. To ensure industrial-scale applications, a multidisciplinary approach involving the relationships between enterprises, academic research centers, and governments is important. In addition, the development of magnetic nano-adsorbents that are selective for specific industrial applications should be prioritized. Exploring these materials for also pollutant, as previous studies have removed multiple contaminants simultaneously

CONCLUSIONS

This review emphasizes the great potential of iron oxide nanoparticles (IONPs) in a range of applications, especially biomedicine and environmental remediation. Understanding the composition, structure, and thermal stability of IONPs is essential for optimizing their functionality and efficacy.

1. One of the primary issues with conventional water treatment procedures is the removal of a wide range of pollutants, which can be effectively addressed by IONPs because of their special magnetic properties.
2. Improved pollutant adsorption and recovery methods are now possible owing to the considerable improvements in IONP performance and application brought about by synthesis methodology innovations, such as green synthesis and surface functionalization.
3. The scalability and economic viability of IONP technologies must be the primary focus of ongoing research to enable their wider use in industrial and municipal wastewater treatment systems.
4. Ultimately, addressing the global water crisis and preserving a healthy planet for future generations requires the implementation of iron oxide nanoparticles.

ABBREVIATIONS

AOPs	Advanced oxidation processes
CED	Cathodic Electrochemical deposition
$CFU.mL^{-1}$	Colony-forming units per milliliter
EAOPs	Electricity-driven advanced oxidation processes
IONMs	Iron oxide nanomaterials
MION	Magnetic iron oxide
MMM	Mixed matrix membrane
MNMs	Micro/nanomotors
MOFs	Metal oxide frameworks
MONPs	Metal oxide nanoparticles
MXI	MXene Iron oxide
N-N	Nitrate or nitrite
PAA	Polyacrylic acid
PEG	Polyethylene glycol
PEI	Polyethyleneimine
PVDF	Polyvinylidene fluoride
RO	Reverse Osmosis
ROS	Reactive oxygen species
SPIONs	Superparamagnetic iron oxide nanoparticles
TKN	Total Kjeldahl nitrogen
TP	Total phosphorous
UFM	Ultra filtration membranes
W&WT	Water and wastewater treatment methods

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