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Comprehensive Review on Wastewater Treatment using Nanoparticles: Synthesis of Iron Oxide Magnetic Nanoparticles, Publication Trends via Bibliometric Analysis, Applications, Enhanced Support Strategies, and Future Perspectives

M. N. Mohammed[1], Oday I. Abdullah[1,2,3,], Muhsin Jaber Jweeg[4], H. S. S. Aljibori[5] , Thamer Adnan Abdullah[6], Nabil Majd Alawi[3], Rashed T. Rasheed[6], Faiza Meharban[7], Husam Talib Hamzah[8], Qusay Al-Obaidi[6]*

[1]Gulf University, Bahrain
[2]AlNaji University, Baghdad, Iraq
[3]University of Baghdad, Iraq
[4]Al-Farahidi University, Iraq
[5]University of Warith Al-Anbiyaa, Iraq
[6]University of Technology, Iraq
[7]Donghua University, China
[8]Andhra University, India
*Correspondence: E-mail: oday.abdullah@tuhh.de

ABSTRACT

This article explored the effectiveness of Iron oxide magnetic nanoparticles (IONPs) in removing pollutants from wastewater generated by various industrial and agricultural sources. We explained the synthesis methods for superparamagnetic IONPs and supported IONPs, providing recent examples from the literature that illustrate their efficacy in producing nanoparticles suitable for wastewater treatment. We also discussed the application of these magnetic nanoparticles in removing a range of pollutants, including dyes, heavy metals, pharmaceuticals, and small organic molecules, highlighting the potential of various types of IONPs in wastewater remediation. Bibliometric analysis was also used, helping us understand the developmental nuances of a specific field and highlights emerging areas. Furthermore, we investigated modifications to IONPs and the creation of composites with organic and metal supports to enhance their adsorption capacity and recyclability. Lastly, we addressed the environmental impact and safety considerations associated with using IONPs in wastewater treatment, emphasizing the need for further research to tackle these issues. Overall, this comprehensive review provides valuable insights into applying IONPs in wastewater treatment, from the direct use of IONPs to enhanced supported IONPs, paving the way for sustainable and efficient water purification to promote a healthier environment.

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1. INTRODUCTION

Since the beginning of the era of the Industrial Revolution which is a double-edged sword, the scarcity of pure water for drinking and other amenities made it challenging to provide people with clean water [1]. One of the main causes of water pollution is the improper dumping of industrial-contaminated water in mainstream water bodies, this water contains radionuclides, organic dyes, volatile organic compounds (VOCs), heavy metals, poly acyclic aromatic hydrocarbons (PAHs), pharmaceutical chemicals, pesticides, etc. [2]. Some of these are biodegradable while others are non-biodegradable pollutants and pose serious health risks for human health. The majority of these pollutants are carcinogens, genotoxins, teratogens, or hepatotoxins which is the major concern for children as well as adults. Consequently, remediation of water pollution is necessary to ensure public health and environmental stability [3, 4].

Many reports regarding water treatment have been well-documented (**Table 1**). Membrane filtration, precipitation, chemical processing, coagulation and flocculation, ion exchange, biological methods, and adsorption are among the most common technologies employed for wastewater treatment (WWT) [5, 6]. However, adsorption is one of the most suitable techniques to target various contaminants in wastewater. Researchers are on a continuous quest to mitigate the challenges associated with WWT, such as disposing of massive waste generated in precipitation, getting rid of secondary metabolites as a product of chemical processing, dealing with noxious sludge obtained during coagulation, fouling during membrane filtration, lacking affinity in biological methods, and cost competency of the processes [7]. Numerous advanced composite materials comprising silica, clay, carbon, zeolite, and magnetic oxide nanoparticles have been recently employed for WWT as adsorbents. The utilization of magnetic nanoparticles (MNPs) offers numerous advantages, underscored by their distinctive properties and versatile responses. MNPs especially superparamagnetic iron oxide magnetic nanoparticles (SPIONPs) exhibit a high specific surface area, facilitating strong interactions with molecules and ions due to their favorable surface-to-volume ratio [8, 9]. These characteristics, coupled with their high absorption efficiency, render them highly effective in WWT applications. Furthermore, SPIONPs have penetration resistance, attributed to their ability to eliminate internal absorption surfaces in porous adsorbents, ultimately enhancing their efficacy in adsorption processes, especially in WWT. Additionally, iron oxide magnetic nanoparticles (IONPs) can be efficiently removed from water post-treatment due to their magnetic character through the application of magnets, enabling easy separation and reuse of these IONPs [10, 11].

Table 1. Previous studies relating to water treatment.

No	Title	Technique used for wastewater treatment	Ref
1	Membrane bioreactor for domestic wastewater treatment: Principles, challenges, and future research directions.	Domestic wastewater treatment	[12]
2	Changes of heavy metal concentrations in Shitalakhya river water of Bangladesh with seasons.	Seasonal heavy metal changes	[13]
3	Monitoring heavy metal contamination levels and microbiological pollution in seawater of Agadir coastal zones.	Heavy metal contamination	[14]
4	The comparison of electrodialysis and nanofiltration in nitrate removal from groundwater.	Nitrate removal methods	[15]
5	Performance and energy consumption evaluation of rotating biological contactor for domestic wastewater treatment.	Energy use in wastewater treatment	[16]

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Table 1 (continue). Previous studies relating to water treatment.

No	Title	Technique used for wastewater treatment	Ref
6	Physico-chemical investigation of wastewater from the Sebdou-Tlemcen textile complex in North-West Algeria.	Textile wastewater analysis	[17]
7	Assessment of iron contamination in groundwater of catchment area water.	Iron contamination in groundwater	[18]
8	Step-by-step fabrication of PVDF-TiO2 hollow fiber membrane and its application desalination of wetland saline water via pervaporation	Desalination membrane fabrication	[19]
9	Effect of water regime and soil maintenance mode on vegetative growth and peach tree production	Peach tree growth factors	[20]
10	Real time water quality monitoring system for smart city in Malaysia.	Real-time water monitoring	[21]
11	Assessment and optimization of coagulation process in water treatment plant: A review.	Water coagulation optimization	[22]
12	Effect of substrate and water on cultivation of Sumba seaworm (nyale) and experimental practicum design for improving critical and creative thinking skills of prospective science teacher in biology and supporting sustainable development goals (SDGs).	Seaworm cultivation methods	[23]
13	Design-construction of a solar cell energy water pump as a clean water source for people in Sirnajaya village, Gununghalu district.	Solar water pump design	[24]
14	Design of micro-controlled swimming pool water quality monitoring system with SMS notification for educational purposes with cost analysis.	Pool water monitoring system	[25]
15	A step-by-step experimental procedure for water quality assessment of blue lagoon: Comparison to socio-demographic and economic profile for a teaching model.	Water quality teaching model	[26]
16	Improvement of the technology of industrial wastewater treatment in the mining industry.	Industrial wastewater treatment	[27]
17	Plastic in water and its implications in human and biological systems.	Plastic impact on water	[28]
18	Education of dietary habit and drinking water quality to increase body immunity for elementary school.	Dietary habits and immunity	[29]
19	Performance investigation of surface modified ceramic microfiltration membranes of ionic water treatment.	Ceramic membrane performance	[30]
20	Emulsion liquid membrane (ELM) enhanced by nanoparticles and ionic liquid for extracting vanadium ions from wastewater.	Vanadium extraction with ELM	[31]
21	A comprehensive analysis of the hydrogen generation technology through electrochemical water and industrial wastewater electrolysis.	Hydrogen generation via electrolysis	[32]
22	Biodegradability enhancement of oily wastewater by an SBR treatment methods.	Enhancing oily wastewater biodegradability	[33]
23	Anticancer properties of titanium dioxide (TiO2) nanoparticles obtained from Quercus infectoria plant extract.	TiO2 nanoparticles' anticancer properties	[34]
24	Effect of magnesium oxide nanoparticles (Mgo) on wastewater treatment and electric current generation using microbial fuel cell technology.	MgO in wastewater treatment	[35]

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Different iron oxides particularly magnetite (Fe_3O_4) have been extensively explored as a remediation agent in advanced oxidation processes for small organic molecules, magnetized coagulation, and as an effective adsorbent for the removal of pollutants from wastewater. Iron oxide nanoparticles (IONPs) composed of magnetite have been investigated extensively for their size and shape control, as well as their non-toxic properties after the treatment. Magnetite which is a combination of Fe(II) and Fe(III) salts during co-precipitation under basic conditions results in unique magnetic characteristics and exceptional absorption capabilities for pollutants [36] As one of the most abundant oxides in iron ores, magnetite's utilization offers a sustainable and cost-effective alternative in WWT, leveraging iron's abundance as the most prevalent transition metal for the synthesis of adsorbents to remove pollutants from water [37]. IONPs magnetic properties, along with their ability to serve as a recyclable heterogeneous catalyst/adsorbent, not only facilitate toxin absorption and removal but also enable the conversion of toxins into value-added products for after-use [38, 39]. While pure IONPs without the addition of any supports or other metal referred to as SPIONPs have been extensively studied WWT, they often exhibit lower activity compared to other metal nanoparticles or hybrid systems. To address this issue, various immobilization/modification methods have been developed to anchor active metals onto the surface of the magnetic nanoparticles or to mix the IONPs with other metals. By using IONPs as a core and immobilizing active metals on the surface or the other way around, adsorption ability can be enhanced. Furthermore, employing IONPs as supports can enhance the stability and recyclability of previously unstable nanoparticles that were very effective but lacked effective recyclability [40, 41]. Additionally, IONPs' precise size and shape control, along with their non-toxic and inert nature, make them a preferred catalyst support in various photocatalytic applications [42].

The purpose of writing this review paper is to extensively explore applications of IONPs in wastewater treatment through in-depth analysis of various recently published research. This work aims to elucidate the effectiveness of IONPs in the removal of different pollutants, including organic/inorganic dyes, heavy metals, pharmaceuticals, and small organic molecules. Additionally, this review highlights the importance of modifications in IONPs in enhancing the adsorption capacity and recyclability by coupling them with other metals or composite materials. By addressing these concerns associated with WWT and providing insights into the potential of IONPs-based WWT, this paper contributes to the advancement of sustainable solutions for water purification by reviewing the most recent progress in the field.

This paper is important, as shown by excellent trends in publication (see **Figure 1**). Detailed information on how to get bibliometric analysis data using Scopus is explained elsewhere [43]. Bibliometric is important [44-46]. Previous studies relating to bibliometrics are explained in **Table 2** and **Figure 1** [44].

Table 2. Previous reports on bibliometric analysis.

No	Title	Focusing Research & Objectives	Ref
1	The latest report on the advantages and disadvantages of pure biodiesel (B100) on engine performance: Literature review and bibliometric analysis	Impact of Pure Biodiesel (B100) on Engine Performance	[47]
2	A bibliometric analysis of management bioenergy research using vosviewer application	Bioenergy Research Management	[48]

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Table 2 (continue). Previous reports on bibliometric analysis.

No	Title	Focusing Research & Objectives	Ref
3	Oil palm empty fruit bunch waste pretreatment with benzotriazolium-based ionic liquids for cellulose conversion to glucose: Experiments with computational bibliometric analysis	Biomass Pretreatment and Cellulose Conversion	[49]
4	Research mapping in the use of technology for fake news detection: Bibliometric analysis from 2011 to 2021	Fake News Detection Technologies	[50]
5	Research mapping in the use of technology for fake news detection: Bibliometric analysis from 2011 to 2021	Fake News Detection Technologies	[51]
6	Management information systems: bibliometric analysis and its effect on decision making	Impact of MIS on Decision Making	[52]
7	Phytochemical profile and biological activities of ethylacetate extract of peanut (Arachis hypogaea L.) stems: In-vitro and in-silico studies with bibliometric analysis.	Phytochemicals and Biological Activity	[53]
8	Biomass-based supercapacitors electrodes for electrical energy storage systems activated using chemical activation method: A literature review and bibliometric analysis	Biomass-Based Supercapacitors for Energy Storage	[54]
9	Antiangiogenesis activity of Indonesian local black garlic (Allium Sativum 'Solo): Experiments and bibliometric analysis	Antiangiogenesis Properties of Black Garlic	[55]
10	Dental suction aerosol: Bibliometric analysis	Dental Aerosol Studies	[56]
11	Bibliometric analysis of nano metal-organic frameworks synthesis research in medical science using VOSviewer	Nano Metal-Organic Frameworks in Medicine	[57]
12	Research trends from the Scopus database using keyword water hyacinth and ecosystem: A bibliometric literature review	Water Hyacinth and Ecosystem Research	[58]
13	Chatbot artificial intelligence as educational tools in science and engineering education: A literature review and bibliometric mapping analysis with its advantages and disadvantages.	Chatbots in Science and Engineering Education	[59]
14	Sustainable Production-inventory model with multimaterial, quality degradation, and probabilistic demand: From bibliometric analysis to a robust model	bibliometric analysis	[60]
15	How technology can change educational research? Definition, factors for improving quality of education, and computational bibliometric analysis	Technology in Educational Research	[61]
16	Effects of sustained deficit irrigation on vegetative growth and yield of plum trees under the semi-arid conditions: Experiments and review with bibliometric analysis	Impact of Deficit Irrigation on Plum Trees	[62]
17	Hydroxyapatite as Delivery and Carrier Material: Systematic Literature Review with Bibliometric Analysis	Hydroxyapatite in Drug Delivery	[63]
18	Development of intelligent tutoring system model in the learning system of the Indonesian national armed forces completed with bibliometric analysis.	Intelligent Tutoring Systems in Military Education	[64]
19	Artificial intelligence (AI)-based learning media: Definition, bibliometric, classification, and issues for enhancing creative thinking in education	AI-Based Learning Media in Education	[65]
21	Bibliometric analysis of high school keyword using VOSviewer indexed by Google Scholar	High School Education Research Trends	[66]
22	Use of blockchain technology for the exchange and secure transmission of medical images in the cloud: Systematic review with bibliometric analysis	blockchain technology	[67]
23	The use of mobile learning in schools as a learning media: Bibliometric analysis	Bibliometric analysis	[68]

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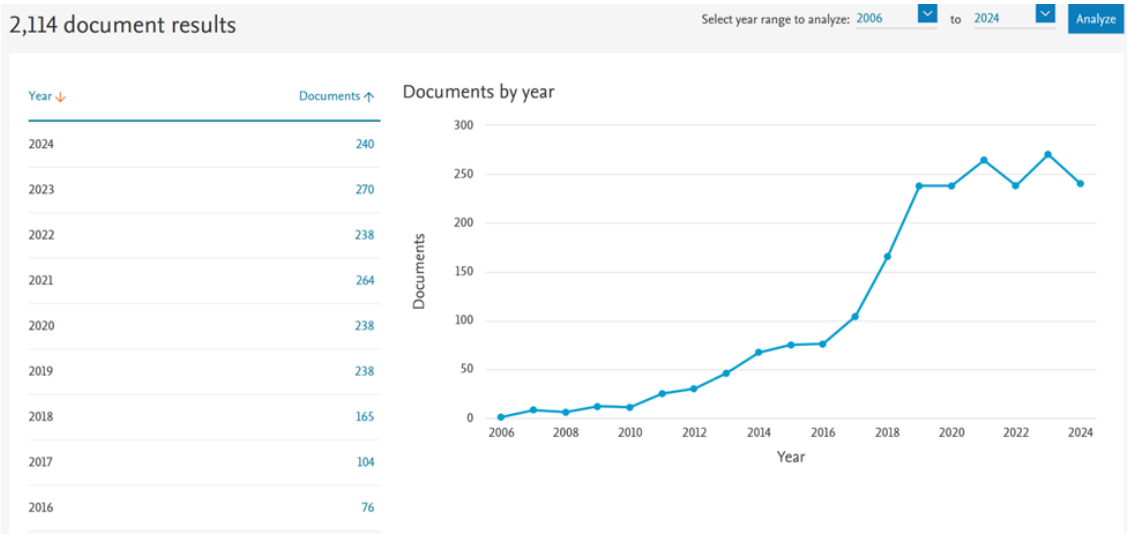

Figure 1. Research trend using keywords "iron oxide nanoparticle wastewater" taken on October 2024.

2. METHODS

To conduct this review, a comprehensive literature survey was performed, focusing on publications related to Iron Oxide Magnetic Nanoparticles (IONPs) and their applications in wastewater treatment. The search was conducted using various academic databases, including Scopus, Google Scholar, and Web of Science, to ensure a broad coverage of relevant studies. The review encompassed literature published from 2010 to 2024, capturing significant advancements and trends in the field. Keywords such as "Iron Oxide Nanoparticles," "wastewater treatment," and "synthesis methods" were utilized to filter the most pertinent articles. This systematic approach allowed for the identification of key research themes, methodologies, and outcomes, providing a solid foundation for understanding the current state of research on IONPs. The findings were then analyzed to highlight gaps in the literature and suggest future research directions.

3. RESULTS AND DISCUSSION

3.1. Synthesis Methods for SPIONPs

To clarify before starting to discuss different methods, where SPIONPs only contain iron and no other supporting metal oxides or materials. Different synthetic approaches have been reported for the preparation of SPIONPs which include chemical, physical, and biological methods. Iron-based nanoparticles can be synthesized in various forms, including magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3), hematite (α-Fe_2O_3), iron oxy-hydroxide (FeOOH), and metallic zerovalent iron (ZVI). Chemical synthesis is favored for its precise control over nanoparticle shape and size. The most commonly used chemical synthesis methods include co-precipitation, hydrothermal, thermal decomposition, microemulsion, and sol-gel technology. Synthesizing SPIONPs is a meticulous and multistep process requiring optimization from the initial design phase, as even minor variations in production parameters can significantly impact the final product [69]. Hence, strict control over both physical and chemical properties is essential to meet diverse application requirements. **Figure 2** provides an overview of some of the commonly used methods to prepare SPIONPs. **Table 3** represents some of the IONPS and their respective synthesis methods and final applications in different industries.

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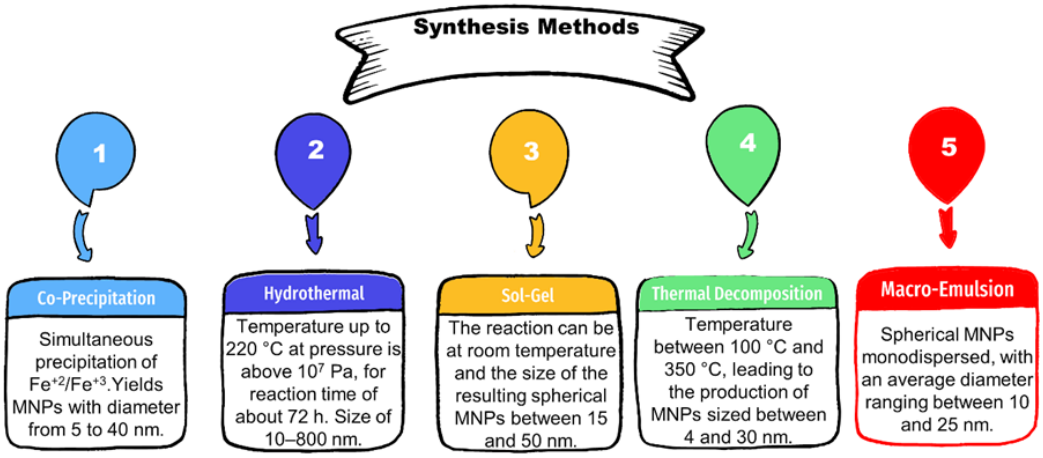

Figure 2. Synthesis methods for Magnetic Iron oxide nanoparticles (MIONPs).

3.1.1. Co-precipitation Method

The co-precipitation method stands out as a widely used approach for synthesizing IONPs, owing to the non-toxic nature of the starting materials typically used. This method exploits the phenomenon of co-precipitation, where a precipitate carries down one or more substances that are typically soluble under these conditions through nucleation and subsequent grain growth. Notably, IONPs can be synthesized using this method under an inert nitrogen (N_2) atmosphere. Co-precipitation synthesis yields IONPs with a broad distribution around diameter ranging from 5 to 40 nm [70, 71]. The physical properties of the resultant IONPs are dependent on various reaction conditions like which type of salts are employed and at what pH the reaction is carried. Shabani *et al*. synthesized Fe3O4 nanoparticles (NPs) utilizing the co-precipitation method and studied their coagulation efficiency in WWT. The synthesized IONPs exhibited purity, with sizes in the range of 22 to 32 nm, and a surface area of 99.6 m^2/g with a pore diameter of 10.6 nm. The application of 0.2 g of synthetic IONPs effectively reduced water turbidity to 100% from an initial turbidity of about 17 NTU at a pH 6 [72]. In another study, Nguyen *et al*., utilized the unique ultrasound-assisted co-precipitation method to prepare magnetite NPs, this method yielded spherical particles with sizes in the range of 10 to 15 nm. These IONP were employed as a magnetic adsorbent for the removal of congo red dye from aqueous solutions [73]. Al-Madhagi *et al*., reviewed various methods for the synthesis of IONPs, utilizing different iron precursors and reaction conditions coupled with surface modifications, aimed at achieving mono-dispersity and superpara-magnetism with diameters less than 30 nm [74].

3.1.2. Thermal Decomposition

Thermal decomposition is a highly effective method for producing magnetic IONPs with narrow size distributions which offer precise control of the mean diameter of particles. This process consists of two main approaches which are; (i) heating-up and (ii) hot-injection. In the heating-up approach, a pre-mixed solution of metal precursor, surfactants, and the solvent is heated until NPs begin to form clusters and grow [75]. In the second approach, hot-injection induces rapid and uniform nucleation by injecting reagents into a hot surfactant solution which is followed by controlled growth. Both these approaches involve heating a precursor mixture in the presence of organic solvents and surfactants. Iron carbonyls and acetylacetonates are commonly used non-magnetic precursors, while mostly fatty acids serve as surfactants, excluding oleic acid. Argon/Nitrogen is essential for maintaining an inert

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atmosphere during the reaction [76]. The optimum temperature ranges from 100 °C to 350 °C, resulting in the production of crystalline IONPs with diameters of 4 to 30 nm [77]. Control over temperature and reaction time is crucial for regulating the size of IONPs. Bhole *et al*. used the thermal decomposition method to synthesize magnetite nanoparticles and named as SS–Fe_3O_4-NPs using the extract of Sargassum spp. Which is a readily abundant marine macroalgae found in the Western coastal region of India. These magnetite nanoparticles demonstrated exceptional catalytic efficiency in degrading methylene blue dye, achieving a remarkable 98% degradation within 25 minutes [78]. Effenberger *et al*., explored thermal decomposition of iron (III) acetylacetonate in the presence of different surfactants to explain their roles and find economically viable alternatives for synthesizing IONPs while controlling their size and shape. It was discovered that certain affordable surfactants, such as 1,2-octanediol and cyclohexanol can substitute the commonly used expensive 1,2-hexadecanediol, offering a cost-effective pathway for producing high-quality magnetic nanoparticles [76].

3.1.3. Hydrothermal Method

The hydrothermal method offers a versatile method for synthesizing a wide range of IONPs. This method involves a system comprising solid metal oxides, precipitation agents and a water-ethanol solution under high-temperature and high-pressure conditions. Hydrothermal synthesis is conducted at temperatures around 100220°C and pressures exceeding 10^7 Pa, with a total reaction duration of up to 72 hours [79]. Inside a Teflon-lined stainless-steel autoclave, a temperature gradient is established which facilitates the deposition of the mineral solute and growth of the desired NP. This technique yields NPs with uniform shape and size which are adjustable from a few nanometers to several hundred nanometers. Notably, NPs with small diameters are desirable for optimal magnetic properties, the upper limit of formation of NPs is around 80 nm [80, 81]. Particle size and distribution are greatly influenced by precursor concentration, reaction time, and temperature [82]. Additionally, the hydrothermal Technique is eco-friendly and versatile, requiring no organic solvents or post-treatments. Jesus *et al*., in a recent study comparatively investigated the synthesis and magnetic characteristics of IONPs, examining two commonly used synthesis methods; co-precipitation and hydrothermal using sucrose as a chelating agent. Transmission electron microscopy (TEM) analysis reveals spherical-like particles with an average size ranging from 3 to 10 nm in both cases with higher magnetic properties which were tested for the dye removal from wastewater [83].

3.1.3. Micro-Emulsion Method

The microemulsion is a stable dispersion of two immiscible solvents in the presence of a surfactant, forming a monolayer at the immiscible solvents interface exhibiting extremely low interfacial tension between two layers. Within microemulsions, IONPs are synthesized via intra-micellar nucleation and growth by following a standard procedure [84]. The physicochemical properties of nanoparticles synthesized through this method primarily hinge on the choice of surfactant. Typically, these nanoparticles exhibit a spherical shape, and near-monodisperse distribution, with diameters ranging from 10 to 25 nm [85]. Water-in-Oil (W/O) microemulsions are commonly used as reverse micelles in this method. Borad *et al*., synthesized maghemite NP within a water-in-oil microemulsion utilizing Sodium dioctyl sulfosuccinate surfactant. The resulting IONPs were used as an adsorbent for hexavalent chromium from water in a batch experiment [86].

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3.1.4. Sol-gel Method

This method of producing IONPs involves the hydroxylation and condensation of precursors, leading to the formation of a colloidal solution known as the "sol" of NPs. Subsequently, this sol is dried or "gelled" through solvent removal, resulting in the formation of a three-dimensional network of iron oxide. Typically, water serves as the solvent in this process, although acids or bases can also be employed to hydrolyze the precursors. The reaction can be performed at room temperature and the size of the spherical IONPS can be adjusted within the range of 15 to 50 nm [87, 88]. Khan *et al*., synthesized ε-Fe_2O_3 using the sol-gel method. X-ray diffraction analysis (XRD) indicated an amorphous state for the samples, even after heat treatment up to 600 °C, at high temperatures, the formation of a fraction of crystalline IO phases was seen. The presence of ε-Fe_2O_3 particles was found to be contingent upon various factors, including particle size, annealing temperature, and initial iron concentration in the chemicals. Optimized conditions for the synthesis of ε-Fe_2O_3-rich samples were determined which resulted in the formation of approximately 90% of the ε-Fe_2O_3 phase with a particle size of 15±0.6 nm [89]. **Table 3** shows a Summarization of Applications of Nanomaterials and different Synthesis methods.

Table 3. Applications of Nanomaterials and Synthesis methods.

Nanomaterials	Synthesis methods	Applications	Ref
γ-Fe_2O_3	Crushing, sieving, solvent extraction, and co-precipitation	Water purification and environmental remediation	[90]
Fe_3O_4	Thermal decomposition and magnetic resonance	Biomedicine and cancer treatment	[91]
Fe_3O_4@AuNPs	Sonochemical method	Breast cancer treatment	[92]
Fe_3O_4NPs	A simple rapid stabilization method	Breast cancer treatment	[92]
Fe_3O_4@AuNPs	Sonochemical method	Magnetic resonance imaging (MRI) and CT scan	[93]
Fe_3O_4@AuCS	Rapid sonochemical synthesis	Cancer cell eradication and biomedical applications	[94]
Fe_3O_4NPs, AuNPs & Fe_3O_4@AuNPs	Sonochemical method and Response Surface	Drug delivery, MRI, and Biomedical applications	[95]
Fe_2O_3; Suspension	Humic acid leaching and absorption process	Subsurface water and soil treatment	[96]
FeO_X film tailing	Sputtering and Plasma emission monitoring	Magnetic storage, electric devices, and iron ore tailing applications	[97]
α-Fe_2O_3 and γ-Fe_2O_3	Laser ablation	Hyperthermia application	[98]
Fe_3O_4	thermal decomposition	Magnetic storage, electric devices, and iron ore tailingapplications	[99]
$Fe(CO_3)$	thermal decomposition	X-ray scattering, Magnetic data storage Magnetic Reso-nance Imaging (MRI)	[100]
Fe_3O_4; Magnetic Hydrophobic	Biosynthesis	Tumor malignant detention and Vivo-Magnetic ResonanceImaging (MRI) process	[101]
Fe_2O_3 and Fe_3O_4 SPION	Chemical co-precipitation	Biomedical and Magnetic Resonance Imaging (MRI) andMagnetic Particle Imaging (MPI)	[102]
Fe_2O_3	Biosynthesis	Antimicrobial agents and Drug delivery systems	[103]
AuFe3O4 AgFe3O4	Biosynthesis	Antimicrobial testing, Prostate-specific and protein antigendetection	[104]
Fe_3O_4	Biosynthesis	Photocatalytic degradation, Antibacterial agent, and Wastewater filtration	[105]

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3.2. Synthesis Methods for Supported Ionps

Various techniques exist for effectively immobilizing metal nanoparticles (NPs) onto the surface. The selection of a specific method can significantly influence the stability, morphology, and electron mobility of the resulting composite, making it a crucial consideration in catalyst or absorbent design. In this review paper, we explored impregnation, co-precipitation, coating, and grafting methods.

(i) *Impregnation:* Impregnation stands out as a widely utilized method for incorporating a metal catalyst onto magnetic surfaces. It Is characterized by its simplicity and cost-effectiveness, involving the direct precipitation or condensation of the metal NPs onto the magnetic support (IONPs) [106]. However, this method does not use a stabilizer, which can result in challenges related to reproducibility of shape and size. Consequently, more intricate techniques have been explored to introduce greater control over the impregnation process [107].

(ii) *Co-Precipitation:* Similar to the synthesis of SPIONPs using the co-precipitation method, the IONPs with a support can also be prepared by using this method which involves blending the active metal which can be titanium for photo-catalysis or any other metal and supports (which in this case can be IONPS) to facilitate the formation and growth of a solid precursor comprising both the active metal and support. This process involves solvent evaporation which is followed by heat treatment, which results in well-distributed metal oxide domains on the magnetic surface (IONPs). This one-step approach can achieve very high loadings of active metal while maintaining a small particle size, making it a favored choice for catalyst production with high loadings [108]. However, nucleation is sensitive to changes in reaction conditions, which can lead to non-uniform growth or the precipitation of different phases within the NP cluster [109].

(iii) *Coating:* Coating serves as a widely adopted technique to address issues that arise with bare magnetite (IONPs). The core is encapsulated and stabilized using some suitable substances which is followed by the precipitation of the metal catalyst onto different surfaces. Silica emerges as a prominent choice for coating magnetite due to its eco-friendly nature, cost-effectiveness, and widespread availability [110]. Typically achieved through the sol-gel method, this process involves applying a second layer containing an active metal. While the addition of a stabilizer enhances the robustness of the catalyst, it also leads to a significant increase in size, subsequently reducing the surface area-to-volume ratio and impacting the activity of the magnetic nanoparticle [111].

(iv) *Grafting:* In addition to silica, customized ligands can serve as linkers between the IONPs core and an active metal other than iron in the grafting method [112]. This approach is designed to protect the IONP core from over-oxidation and enhance its stability. Carefully chosen ligands can be used to fine-tune the selectivity, electron movement, and activity of the IONPs. However, this technique does incur additional costs associated with the production of these IONPs [113].

3.3. Wastewater treatment with IONPs

After assessing the primary methods for manufacturing superparamagnetic and supported magnetic nanoparticles, this section delves into the removal of various organic and inorganic pollutants from WW. Subsequent sections will present several studies where these SIONPs have been utilized in treatment processes, including different removal methodologies like adsorption and coagulation/flocculation [114]. Water and wastewater contaminants typically fall into three main categories: pathogenic microorganisms, toxic organic compounds, and

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inorganic substances. Wastewater from diverse sources carries a multitude of potent pollutants. For instance, non-biodegradable dyes originating from the textile, paint, and leather industries are significant environmental pollutants. Heavy metals are also commonly present in wastewater from various industries, posing potential toxicity and carcinogenic risks to both humans and aquatic ecosystems [115, 116].

3.3.1. Dye Removal

Textile industry dyes such as methylene orange (MO), methylene blue (MB), and Rhodamine B (RhB) pose significant environmental as well as health risks because of their toxicity, mutagenic and carcinogenic effects. Their chemical and biological stability makes them difficult to eliminate. However, Fe_3O_4 nanoparticles, synthesized through diverse methods, have shown efficacy in degrading such organic compounds. Damasceno *et al*. studied SPIONPs synthesized via chemical co-precipitation, followed by an investigation into their adsorption performance for indigo carmine (IC) dye. Optimal parameters included for dye removal were pH 4.0, contact time of about 150 mins, and dye concentration of 20 mg/L. The maximum adsorption capacities (qm) were found to be 17.45 mg/g. These SPIONPs exhibited significantly higher IC removal efficiency of around 87%. Following IC dye desorption, the NP successfully recovered from the solution and reused up to 5 times without any significant losses in efficiency (**Figure 3**) [117]. In another recent study, Raja *et al*. synthesized SPIONPs via the chemical precipitation method, and its efficiency in removing different dyes from aqueous solutions was assessed. Various parameters were investigated, including dye and adsorbent concentrations, contact time, pH, and temperature on the removal efficiency. Results showed rapid dye removal upon external adsorption influence. Experimental data aligned well with Langmuir's isotherm and pseudo-second-order kinetics, indicating a maximum qm of 394.5 mg/g [118].

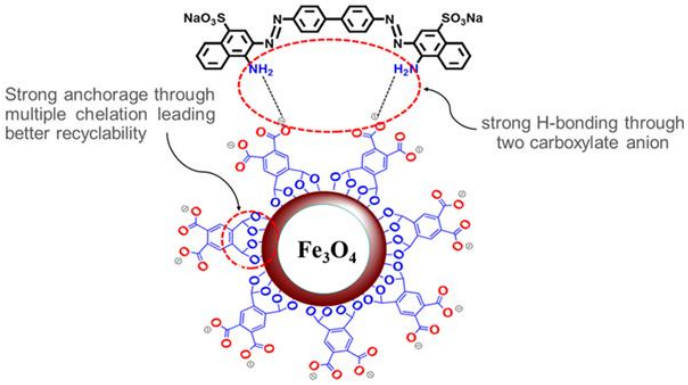

Figure 3. Schematic illustration of Fe_3O_4@BTCA material adsorption towards Congo red dye through H-bonding carboxylate anions.

While these SPIONPs demonstrate potential in WWT, performance can further be enhanced through modification with carbon base supports or immobilization of additional active metal catalysts on their surface. These supports can be laboratory-synthesized carbon and silica supports, as well as recycled materials sourced from waste or agricultural sources. Some of the laboratory-synthesized supports include montmorillonite (MMT), carbon nanotubes (CNTs), activated carbon (AC), mesoporous carbon (MC), and silica serving as supports for Fe3O4. Recently, Wang *et al*. synthesized an adsorbent composed of CoFe2O4/chitosan (CS) and supported it onto alkalized MXene sheets using hydrothermal and self-assembly methods. Batch experiments were conducted to evaluate the qm for Rhodamine B (RhB), Congo Red (CR), and Malachite Green (MG) dyes. The incorporation of

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$CoFe_2O_4$/CS into alk-MXene support enhanced the qm for these dyes. Optimum parameters for the best performance were 4-hour etching time which resulted in an ultra-high adsorption capacity of 2095.9 mg/g, 1333.9 mg/g, and 537.6 mg/g for CR, RhB, and MG dyes, respectively. Analysis of the adsorption mechanism showed synergistic effects of (i) electrostatic interaction, (ii) π-π interaction, and (iii) hydrogen bonding which contributed to the higher adsorption of the alk-MXene/$CoFe_2O_4$/CS [119]. In another recent study, Mohamad *et al*., synthesized IONPs supported on activated carbon through the co-precipitation method using commercial activated carbon. This nanocomposite was used as an adsorbent for the removal of Mordant Violet 40 (MV40) dye from wastewater. Remarkably, CAC-IO achieved a maximum removal efficiency of 99.92% for MV40 dye at a starting concentration of 100 mg/L, adsorbent dose of 1.0 g/L, pH of about 2.07, and contact time of 3 hours. The adsorption of MV40 dye followed the Freundlich isotherm model, indicating favorable adsorption behavior [120].

3.3.2. Heavy Metal Removal

Pollutants posing significant threats to human health and food security include heavy metals, which are discharged from various sources such as metallurgical operations, mining activities, chemical plants, metal refineries, agricultural practices, and household wastewater. These metals, including lead (Pb), mercury (Hg), molybdenum (Mo), chromium (Cr), zinc (Zn), arsenic (As), and selenium (Se), among others, present serious health hazards. Exposure to these pollutants can result in adverse health effects such as kidney failure, neurological damage, cancer, respiratory issues, and other health complications [121]. Haris *et al*., synthesized SPIONs using a hydrothermal technique and utilized them for the removal of arsenite (As(III)), both in their original form and when encapsulated in alginate beads (SPIONs-Alg). The size of the SPIONs was determined to be around 25 nm with zero coercivity in the magnetization curve, indicative of superparamagnetism. Optimal removal percentages of 99% and 90% were achieved for unsupported SPIONs and SPIONs-Alg, respectively at pH 7, temperature 30°C, and 6.5 mg/L As(III) concentration. The equilibrium data was matched best with the Langmuir isotherm model compared to the Freundlich model. Evaluation of the As(III) qm yielded values of 11.89 mg/g for un-supported SPIONs and 240.081 mg/g for SPIONs-Alg which was determined by the Langmuir adsorption isotherm [122].

Lei *et al*., synthesized Fe_3O_4@DA-DMSA through the functionalization IONPs using dopamine (DA) and 2,3-dimercaptosuccinic acid (DMSA) which is a detoxifying agent for heavy metals. These nanoparticles demonstrated high adsorption capacities for Pb^{2+}, Cu^{2+}, and Cd^{2+} ions, with maximum adsorption capacities of 187.62, 63.01, and 49.46 mg/g, respectively. FDDMs showed superior Pb^{2+} removal compared to the other reported IONPs. In real wastewater and multi-component simulated water samples contaminated with Pb^{2+}, Cu^{2+}, and Cd^{2+}, FDDMs exhibited robust removal capabilities for Pb^{2+} with minimal interference from ionic strength and other ions, demonstrating excellent selectivity (Figure 4a) [123]. In another study, Sharif *et al*., synthesized chitosan-IONPs using the coprecipitation method to effectively remove nickel (Ni) and cobalt (Co) from aqueous solutions. Adsorption experiments showed that under optimal conditions of pH = 6, contact time = 2 h, and adsorbent dosage = 2 g/l, these IONPs exhibited high qm of 30.03 mg/g for Ni^{2+} ion and 53.19 mg/g for Co^{2+} ion [124]. In a very recent breakthrough study, Kothavale *et al*., modified IONPs with thiol (–SH) and carboxylic (–COOH) groups using meso-2,3-dimercaptosuccinic acid (DMSA). These IONPs-DMSA nano-adsorbent was employed for the simultaneous removal of multiple metals such as Pb(II), Ni(II), and Cd(II) from water. These NPs with high mono-disparity and with the size of 8.24 ± 1 nm exhibited the pure magnetite phase. The maximum

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q_m for the removal of Pb(II), Ni(II), and Cd(II) in was found to be 64.5, 53.9, and 27.18 mg/g, respectively. In separate metal systems, the q_m values for Pb(II), Ni(II), and Cd(II) further increased to 116.54, 102.73, and 75.48 mg/g, respectively as shown in **Figure 4b and c** [125]. In another study, IONPs@SiO_2-(-NH_2/-COOH) nanoparticles were synthesized for the removal of Cd^{2+}, Pb^{2+}, and Zn^{2+} ions from water. Thorough characterization revealed that IONPs@SiO2-(-NH2/-COOH) have a superparamagnetic core-shell structure. The surface of IONPs was coated with silica and further modified with amino-carboxyl groups. This improved particle dispersion and the surface area of IONPs@SiO2-(-NH2/-COOH) was about 67.8 m2/g. The q_m of IONPs@SiO_2-(-NH_2/-COOH) for these metals was in the order Pb^{2+} > Cd^{2+} > Zn^{2+} at adsorption dose of about 0.8 g/L, temperature 30°C, and concentrations of metal ions in the solution Pb^{2+}, Cd^{2+}, and Zn^{2+} around 120, 80, and 20 mg/L, respectively. The maximum q_m for Pb^{2+}, Cd^{2+}, and Zn^{2+} were 166.67, 84.03, and 80.43 mg/g, respectively (**Figure 4d**) [126]. Some heavy metal contaminants in the water and the IONPS used for their removal are shown in **Table 4**.

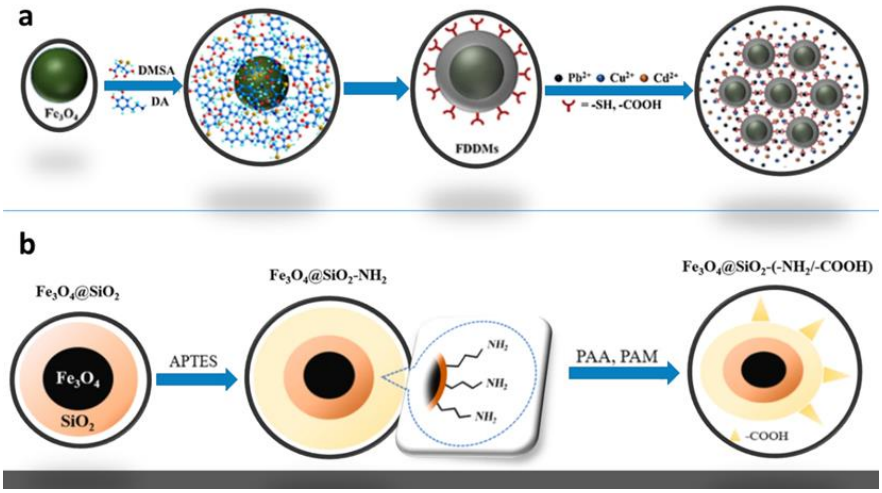

Figure 4. Removal of heavy metals: (a) preparation of FDDMs and its process of removing heavy-metal ions, (b) Effects of pH on the adsorption capacity (qe) of Pb(II), Cd(II), and Ni(II) by MNP-DMSA nano adsorbents (initial metal ion concentration = 10 mg/L, adsorbent dose = 0.1 g/L, and contact time = 60 min), (c) Effects of adsorbent dose on the adsorption capacity (qe) and removal efficiency (R) of Pb(II), Cd(II), and Ni(II) by the MNP-DMSA nano adsorbents (pH = 7, initial metal ion concentration = 10 mg/L, and contact time = 60 min), (d)General structural information of the composition of Fe_3O_4@SiO_2-(-NH_2/-COOH).

Table 4. Studies using a variety of types of iron oxide in removing water contaminants.

Type of iron oxide	Particle size (nm)	Surface area (SBET, m^2/g)	Saturation magnetization (emu/g)	Water contaminant	Optimal adsorption conditions	Adsorption capacity (mg/g)	Removal efficiency (%)	Ref
Mixture of γ-Fe_2O3 and Fe_3O_4	5.25	301.54	55	Cu	pH = 2.5, contaminant concentration = 50 mg/ L, contact time = 10 min, adsorbent dose = 1 g/L, agitation speed = 200 rpm	11.12	90	[127]

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Table 4 (continue). Studies using a variety of types of iron oxide in removing water contaminants.

Type of iron oxide	Particle size (nm)	Surface area (SBET, m^2/g)	Saturation magnetization (emu/g)	Water contaminant	Optimal adsorption conditions	Adsorption capacity (mg/g)	Removal efficiency (%)	Ref
γ-Fe_2O_3	23.5	145.5	35.5	Arsenic	pH = 7.21, contaminant concentration = 40 mg/ L, contact time = 3 h, adsorbent dose = 0.2 g/ L	12.74	95	[128]
Fe_3O_4	10–25	46	83	Arsenic	pH = 5, contaminant concentration = 100 mg/ L, contact time = 3 h, adsorbent dose = 0.5 g/ L, Temp = 25 ◦C	90	-	[129]
Fe_3O_4 modified with sugarcane bagasse biochar	30–100	16.18	55.91	Cr (VI) ions	pH = 4.61, contaminant concentration = 120 mg/ L, contact time = 24 h, adsorbent dose = 1 g/L, Temp = 30 ◦C	71.02	–	[130]
Fe_3O_4 modified with PAC from pistachio waste	30–40	405.57	11.9	Cu (II)	contaminant concentration = 100 mg/ L, contact time = 24 h, adsorbent dose = 10 g/L, Temp = 25 ◦C, agitation speed = 150 rpm	23.61	98	[131]
Fe_3O_4 modified with carboxymethyl- β-cyclodextrin polymer	83	-	-	Lead (II) ions	pH = 5.5, contaminant concentration = 300 mg/ L, contact time = 1 h, adsorbent dose = 2.4 g/ L, Temp = 25 ◦C,	64.2	98	[132]
α-Fe_2O3modified with sodium alganite	16–24	5.43	-	Lead (II) ions	pHPZC = 6 solution pH = 6, contaminant concentration = 0.2 mg/	564	-	[133]

3.3.3. Pharmaceutical Removal

Pharmaceuticals and by-products of the pharmaceutical industry are prevalent pollutants in water, primarily stemming from household disposal practices or industrial processing as shown in **Figure 5**. Their presence poses significant concerns due to their potential long-term exposure, linked to adverse health effects such as behavioral alterations, cell proliferation inhibition, and reproductive system damage. Additionally, pharmaceutical residues pose

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environmental risks by disrupting natural ecosystems, either by eliminating crucial microorganisms or fostering the proliferation of drug-resistance in micro-organisms. Among the common pharmaceutical pollutants are norfloxacin (NFX), ibuprofen (IBP), carbamazepine (CBZ), acetaminophen (APAP), and pantoprazole [134]. These compounds often evade conventional wastewater treatment methods, prompting research into alternative removal or degradation strategies such as absorption or photocatalysis [135]. Notably, IONPS and supported IOPNS, owing to their magnetic properties, have emerged as promising candidates for the removal of these pharmaceutical pollutants from wastewater. Rocha *et al*., synthesized IONPs supported over activated carbon (AC) derived from primary paper sludge. A fractional factorial design was employed to assess key impact of key variables on IONPS/AC properties and its qm efficiency for pharmaceuticals; amoxicillin, CBZ, and diclofenac from wastewater. Notably, four IONPS/AC variants exhibited high adsorption capacities (61-84%) and efficient recovery using a permanent magnet at low IONPs/AC doses (35 mg L−1) [136].

In a recent study conducted by Silva *et al*., synthesized magnetic beads using IONPs comprising alginate/polypyrrole/$ZnFe_2O_4$ referred to as Alg/PPy/$ZnFe_2O_4$ and evaluated their qm towards acetaminophen (ACT) and ibuprofen (IBU) under an external magnetic field (EMF). Batch experiments demonstrated rapid adsorption kinetics, with Alg/PPy/$ZnFe_2O_4$ achieving high qm for the ACT and IBU of 106.7 and 108.2 mg/g, respectively; within a short time of 60-70 mins. The application of an EMF notably enhanced the adsorption capacity by 14% and 12% for ACT and IBU, respectively. Kinetic analysis indicated a pseudo-second-order adsorption mechanism for both drugs on Alg/PPy/$ZnFe_2O_4$ [137]. A magnetic nanocomposite comprising sugarcane bagasse-derived biochar (BC), nanoscale zerovalent iron (nZVI), and chitosan (CS) was synthesized to assess its efficiency in removing aspirin and carbamazepine (CBZ). Response Surface Methodology–Central Composite Design (RSM-CCD) optimization was employed, considering five variables: adsorbent dose, pH, drug concentration, time, and temperature. Under optimized conditions, ASA removal efficiency reached 97.8%, while CBZ removal was up to 89.32%. Langmuir isotherm models demonstrated monolayer adsorption, and kinetics followed pseudo-first- and pseudo-second-order models for ASA and CBZ, respectively. The mechanism is described in **Figure 5a**. Based on isotherm and kinetic analyses, the interaction mechanisms between BC-CS@nZVI surface and drug molecules are elucidated. I. Hydrogen bonding occurs between drug molecules and the composite's surface functional groups (e.g., carboxylic, hydroxyl). II. π-π interactions involve ASA's benzene ring and CBZ's amino groups interacting with the composite surface's C=O, C=C groups. III. Pore filling occurs as small ASA molecules diffuse into meso/macro pores. IV. Lewis's acid-base interaction involves CBZ's NH_2 as Lewis base and BC-CS@nZVI's oxygen groups as Lewis acid. These mechanisms collectively contribute to drug adsorption [138]. Surface-modified IONPs, functionalized with chitosan (CHI) or diethylamino-ethyl dextran (DEAE-D), were investigated for their interactions with pharmaceutical drugs and model cell membranes. Langmuir isotherms and adsorption measurements using 1,2-distearoyl-sn-glycerol-3-phosphate (DSPA) phospholipid monolayers as cell membrane models revealed significant findings. While diclofenac (DCFN) showed no absorption at the air-water interface, triflupromazine (TFPZ) exhibited a maximum insertion pressure (MIP) of 35 mNm^{-1}. Composite IONPs with drugs displayed larger MIP values, indicating IONPs adsorption on the monolayer with the drugs. Notably, IONPs@DEAE-D:DCFN showed an impressive MIP of 67 mNm^{-1}. The Maximum Insertion Pressure experiments were conducted using a Teflon mini trough equipped with a constant surface area (A = 15.8 cm^2). Initially, the trough was filled with 5 mL of LiCl 10 mM solution. Lipids were then spread across the surface to achieve a surface

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pressure ranging from 8 to 30 mN m^{-1}. Subsequently, injections of $HTFPZ^+$ or $DCFN^-$ and MNPs:$HTFPZ^+$ or $DCFN^-$ were made beneath the lipid monolayer, as illustrated in **Figure 5b** [139].

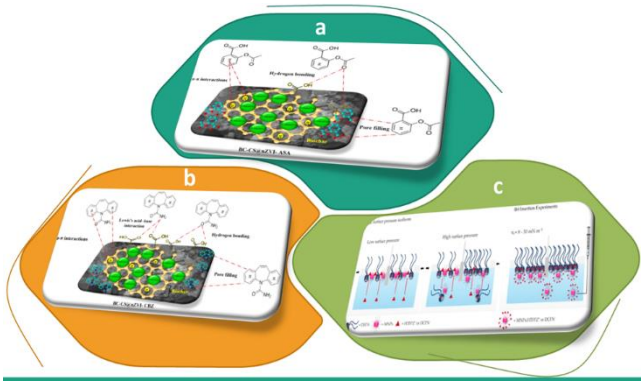

Figure 5. Removal of pharmaceutical components: (a) BC-CS@nZVI and ASA drug molecules, (b) BC-CS@nZVI and CBZ drug molecules, (c) Schematic representation of (a) surface pressure–area isotherm experiments, and (b) insertions experiments.

3.4. Removal of Small Organic Molecules

As discussed in the "Dye degradation" section, organic pollutants pose significant health risks to both humans and the environment due to their resistance to conventional water treatment methods and potential for bioaccumulation. These pollutants consist of polycyclic aromatic hydrocarbons (PAHs), pesticides, and commercial oils. IONPs, characterized by their high surface-to-volume ratio, robust absorption capacity, rapid kinetics, and magnetic separability, offer an effective solution for organic matter removal. Moreover, these NPs can be easily regenerated with minimal secondary waste generation after the WWT [140, 141]. In a study by Ewa *et al.*, the production of magnetic adsorbents with varying porosity characteristics through the carbonization and steam activation of a mixture comprising furfuryl alcohol and iron-containing compounds was demonstrated. The materials exhibit magnetic properties, evidenced by weight loss increments in the neodymium magnet balance test with increasing iron content. Sedimentation tests confirm the enhanced removal efficiency of the used adsorbents facilitated by their magnetic properties. N_2 adsorption isotherms at 77 K reveal distinct porosity differences, with ferrocene promoting mesoporosity and iron(II) sulfate inducing microporosity. XRD measurements further confirmed the presence of magnetite and hematite, with magnetite intensity correlating with saturation magnetization. The PFA-IONPs exhibit high adsorption capacities for Congo red, phenol, atrazine, and isoproturon, with adsorption strongly linked to adsorbent porosity as shown in **Figure 6a** [142]. Pereira *et al.*, synthesized two novel materials by impregnating functionalized multi-walled carbon nanotubes (MWCNT–OH and MWCNT–COOH) with IONPs via solution precipitation. Adsorption efficiency was evaluated using 2,4-D and Atrazine pollutants present in the wastewater. Optimal adsorption occurred at pH 2 for 2,4-D and pH 6 for Atrazine, with equilibrium reached within 30 minutes. MWCNT–OH–Mag exhibited superior performance which is attributed to increased Fe-doped sites and favorable molecular interactions (**Figure 6b**). The Sips model accurately described adsorption isotherms, with MWCNT–OH–Mag showing the highest adsorption capacity at 51.4 and 47.7 mg g−1 for 2,4-D and Atrazine, respectively. Leaching and regeneration tests demonstrated high stability in aqueous solutions [143].

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A multidimensional highly efficient SPION@L-Tryptophan (LT)-Cu^{2+}/Cu0 was synthesized via co-precipitation method as illustrated in **Figure 6c** and investigated as nano-photocatalyst for removing aromatic contaminants and azo dyes from WW. The catalytic efficacy of SPION@LT-Cu^{2+}/Cu0 was examined for nitrobenzene, 4-nitroaniline, 4-nitrophenol, MB, MO, and CR in the presence of $NaBH_4$ reducing agent. Moreover, the synthesized nano-photocatalyst demonstrated high efficiency in degrading MB under visible light irradiation. Its efficient catalytic activity, cost-effectiveness, and sustained reusability over multiple cycles establish SPION@LT-Cu^{2+}/C0 as a promising nano-photocatalyst for wastewater treatment [144].

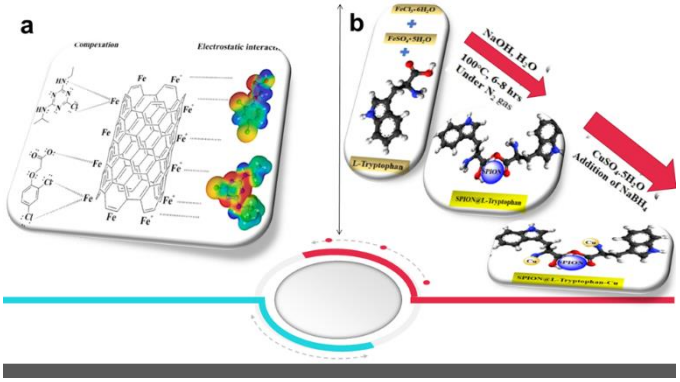

Figure 6. Removal of organic pollutants: (a) Single point adsorption capacity, (b) Plausible mechanisms of interactions between 2,4-D and atrazine pesticides with the Fe atoms that present Fe^{3+}/Fe^{2+} cationic equilibrium behavior in the surface of the MWCNT adsorbents functionalized with $^{-}$OH or $^{-}$COOH, (c) The schematic diagram for the synthesis of novel SPION@L-tryptophan-Cu2+/Cu0 nano-photocatalyst.

3.5. Environmental Impact and Safety

Extensive use of IONPs presents a challenge to explore their econanotoxicity, particularly at higher concentrations. IONPs naturally occur in volcanic eruptions or air pollution. Magnetite and maghemite exist in industrial emissions, traffic smoke, and nanowastes in chemical synthesis plants [145]. Malhotra *et al*. reported reduced toxicity of carbon-coated Fe_3O_4NPs on both behavioral and biochemical responses in adult zebrafish models [146]. The low toxicity can be attributed to the protective effect of carbon coating, decreasing the oxidation and corrosion of IONPs. Conversely, high bioaccumulation of gluconic acid-functionalized γ- Fe_2O_3 (GLA-IONPs) was described in the snail model [147]. Long-term exposure to GLA-IONPs caused higher toxicity, behavioral impairments, and accumulation in *Biomphalaria glabrata*. Henceforth, the ecotoxicological effects of IONPs in bare, coated, or functionalized form must be investigated properly depending on the contaminants and final fate of WWT. As mentioned above researches should emphasize the need to conduct more studies in the area of environmental impact of MIONPs, when used for WWT. Klekotka, U. *et al*. [148] critically discussed the ecotoxicological impact of magnetite NPs on terrestrial and aquatic animals. However, we still lack the literature suggesting standards for using IONPs alone or in combination with other materials for WWT [149].

4. CONCLUSION

In conclusion, the utilization of Iron Oxide Magnetic Nanoparticles (IONPs) holds great promise for addressing the complex challenges associated with wastewater treatment. Through various synthesis methods and surface modifications, IONPs have demonstrated

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remarkable efficiency in removing a wide range of pollutants, including organic dyes, heavy metals, pharmaceuticals, and small organic molecules. Moreover, the development of IONPs materials and with supports further enhanced the adsorption capacity and recyclability of these IONPs which offer sustainable solutions for long-term water purification systems. Despite these advancements, it is important to consider the environmental impact and safety implications of using IONPs in wastewater treatment after their use. Further research is needed to assess the econanotoxicity of these IONPs and establish standards for their use in WWT applications.

Looking ahead, future research in the field of WWT utilizing IONPs should focus on several key areas. Firstly, there is a great need for further exploration of novel synthesis methods and surface modifications to optimize the performance of IONPs in pollutant removal with better efficiency. Moreover, studies should also investigate the scalability and cost-effectiveness of IONPs-based treatment technologies for large-scale utilization. Furthermore, interdisciplinary research efforts are needed to understand the environmental effects and long-term effects of IONPs in aquatic ecosystems for other water base species. Furthermore, the development of multifunctional IONPs systems, such as photocatalytic or membrane-based approaches, holds promise for achieving synergistic pollutant removal and water purification. Overall, continued innovation and collaboration are necessary for harnessing the full potential of IONPs in addressing the global challenges of wastewater pollution and ensuring access to clean and safe water for all.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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