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Review article

Magnetic Nanomaterials in Dye-Contaminated Water Remediation: Recent Advances and Future Prospects

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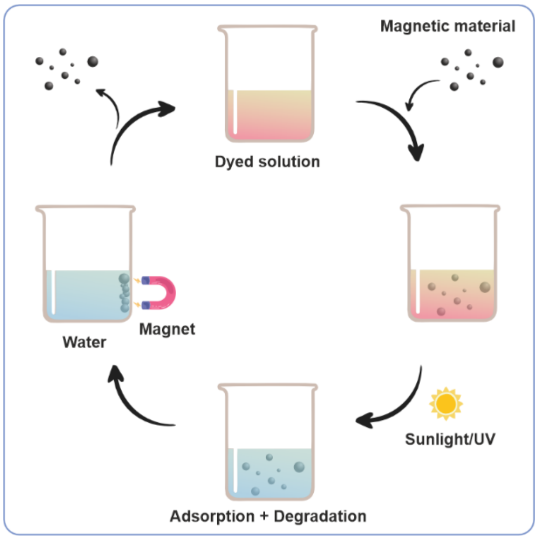
Graphical abstract



Abstract

This review provides a comprehensive analysis of recent advancements in magnetic nanomaterials for dye-contaminated water remediation. The study explores various synthesis methods for magnetic nanoparticles (MNPs), including co-precipitation, thermal decomposition, sol-gel, hydrothermal, and biological approaches. It examines the efficacy of MNPs and their composites in removing diverse dyes from aqueous solutions, highlighting their high adsorption capacities and magnetic separability. The review discusses the development of novel magnetic nanocomposites, such as iron oxide-based materials functionalized with polymers, carbon-based materials, and other functional materials, which demonstrate enhanced performance in dye removal. Adsorption mechanisms, kinetics, and isotherms are analysed, providing insights into the factors influencing dye removal efficiency. The study also addresses the limitations of MNPs, including stability issues, potential toxicity, and challenges in large-scale synthesis. Future research directions are proposed, emphasizing the need for developing more stable, environmentally friendly, and cost-effective magnetic nanomaterials for sustainable water treatment solutions. This comprehensive review contributes to the growing body of knowledge on advanced materials for environmental remediation and highlights the potential of magnetic nanomaterials in addressing global water pollution challenges.

Keywords: Magnetic nanoparticles; Nanomaterials; Textile dyes; Magnetism; Composites

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1. Introduction

The textile industry is one of the world's greatest sectors, but it produces enormous quantities of dyes, toxic metal components, and chemicals in released wastewater (Kadhom et al., 2020). Textile wastewater discharges are harmful wastes that include poisonous complex constituents. If they are not managed appropriately, they can damage aquatic environments and adversely impact human health (Ahmed et al., 2020). The sustainability of the ecosystem is threatened by contaminants from dye wastewater, which prevent environments from carrying out the roles that communities depend on them to do. The textile dyeing sector is responsible for persistent contamination because of the dyes' poor biodegradability and the vivid hue of released wastewater (Hassan and Carr, 2021).

It is estimated that more than 100,000 dyes are used, with the textile sector being the main usage (Amalina et al., 2022). Therefore, disregarding other industries, it is anticipated that the textile industry will release about 300,000 tonnes annually into the streams in upcoming years (Kadhom et al., 2020). Higher levels of alkaline content, biological oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (TSS) with a dye/dm^3 concentration of less than 1 g are the primary features of these effluents (Hynes et al., 2020). Dyes can cause skin irritation, cancer, reduced photosynthesis in aquatic life, and disruption of the delicate ecosystem's equilibrium, among other negative consequences on both plants and animals (Aruna et al., 2021).

The application of magnetic nanoparticles (MNPs) in water treatment is not limited to adsorption. They can also serve as catalysts in advanced oxidation processes, such as Fenton reactions, effectively degrading organic pollutants (Palma et al., 2018; Thomas and Alexander, 2018). Integrating photocatalytic materials with magnetic nanoparticles has been explored to enhance pollutant degradation under light irradiation, providing a dual mechanism for water purification. This approach improves pollutant removal efficiency and allows for the regeneration of the catalytic materials, promoting sustainability in water treatment processes (Thomas and Alexander, 2018; Seo et al., 2017). MNPs have attracted a lot of interest for use in dye degradation processes because of their unique characteristics, which include high surface area, magnetic responsiveness, and catalytic capabilities. These characteristics make MNPs particularly effective in removing various organic dyes from wastewater, critical for environmental remediation. The high surface area of MNPs provides numerous active sites for dye molecules, enhancing the adsorption capacity significantly. For instance, studies have shown that the presence of magnetite nanoparticles can lead to a substantial increase in the adsorption of methylene blue dye, with efficiencies reaching up to 98% in some cases (Modrogan et al., 2021; Mufti et al., 2020).

In addition to adsorption, magnetite nanoparticles play a crucial role in photocatalytic degradation. When exposed to UV light or sunlight, MNPs can generate reactive oxygen species (ROS), such as hydroxyl radicals, which are highly effective in breaking down organic dye molecules (Atta et al., 2020; Reza et al., 2016). This photocatalytic activity has been demonstrated in various studies, where MNPs have been used to degrade dyes like methylene blue and methyl orange under UV irradiation, achieving degradation efficiencies of over 90% (Mbuyazi and Ajibade, 2023). The ability of MNPs to act as photocatalysts is attributed to their electronic properties, which facilitate electron transfer and enhance the generation of ROS. Moreover, the magnetic properties of MNPs allow for easy recovery and reuse after the degradation process. This is particularly advantageous in industrial applications, where separating and recycling catalysts can significantly reduce operational costs and environmental impact (Muzenda and Arotiba, 2022). The superparamagnetic nature of MNPs ensures that they can be easily manipulated using external magnetic fields, making them suitable for continuous flow systems in wastewater treatment. Recent advancements in the functionalization of magnetite nanoparticles have further enhanced their performance in dye degradation applications. By modifying the surface of MNPs with various polymers or other materials, researchers have improved their stability, selectivity, and overall catalytic efficiency. For example, incorporating laccase enzymes onto magnetite nanoparticles has enhanced the decolorization of congo red dye in bioreactor systems, demonstrating the potential for synergistic effects when combining biological and nanomaterial approaches (Sotelo et al., 2022).

This review aims to provide a comprehensive overview of the recent advancements in magnetic composite materials for dye adsorption and photocatalytic degradation. Also, it explores the various types of magnetic composites, their synthesis methods, and their performance in removing different classes of dyes from aqueous solutions. Additionally, this review discusses the mechanisms of dye removal, the factors influencing adsorption and catalytic efficiency, and the potential for practical applications in wastewater treatment. By highlighting the current state of research and identifying future directions, this review seeks to contribute to the development of more effective and sustainable solutions for water purification.

2. Synthesis of magnetic nanoparticles (MNPs)

MNPs have garnered significant attention in various fields due to their unique properties and versatile applications. Several methods can be used to synthesize these nanoparticles, each offering distinct advantages and producing particles with specific characteristics. Fig. 1 and Fig. 2 display different synthesis methods for magnetic nanoparticles. Table 1 tabulates different methods for synthesizing magnetic nanoparticles, their composites, and their respective advantages and disadvantages.

The co-precipitation method is one of the most widely used techniques for synthesizing magnetic nanoparticles. This approach involves the simultaneous precipitation of ferrous and ferric ions in an alkaline medium, typically at room temperature or elevated temperatures. The process is relatively simple and cost-effective, making it attractive for large-scale production. By carefully controlling parameters such as pH, temperature, and reactant concentrations, researchers can tune the resulting nanoparticles' size, shape, and magnetic properties. For instance, magnetite (Fe_3O_4) nanoparticles synthesized via co-precipitation have shown promise in the removal of various dyes from wastewater owing to their high surface area and magnetic separability (Amo-Duodu et al., 2024; Shukla et al., 2021). In a study, red, blue, and yellow printing ink dyes were adsorbed in water-based solutions using Fe_3O_4 nanoparticles prepared by the co-precipitation method. The adsorption percentages of these nanoparticles were around 62%, 97%, and 94%, respectively, in the removal of yellow, blue, and red color (Jannah and Onggo, 2019).

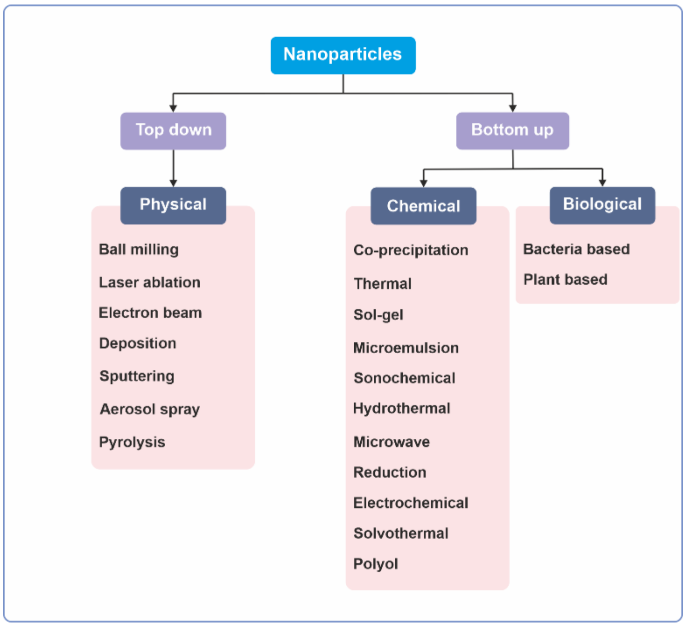

Fig. 1: Different synthesis methods for magnetic nanoparticles.

Another popular method for MNP synthesis is the thermal decomposition technique. This approach involves the decomposition of organometallic precursors in high-boiling organic solvents in the presence of stabilizing surfactants. The thermal decomposition method allows for precise particle size and shape control, resulting in highly monodisperse nanoparticles with excellent crystallinity. Researchers have successfully synthesized a wide range of magnetic nanoparticles, including iron oxides, ferrites, and metal alloys, using this technique. The high quality and uniformity of these nanoparticles make them particularly suitable for biomedical applications and advanced magnetic materials (Niculescu et al., 2022; Zhu et al., 2018). An investigation by Kishore and Jeevanandam, synthesized silica-iron oxide core-shell nanoparticles using the thermal decomposition method for the degradation of rhodamine B in an aqueous solution (Kishore and Jeevanandam, 2012).

The sol-gel method is another versatile approach for synthesizing magnetic nanoparticles. This process involves the formation of a colloidal suspension (sol) followed by its conversion into a gel-like network. The sol-gel technique offers several advantages, including low processing temperatures, high purity, and the ability to produce nanoparticles with controlled composition and structure. Magnetic nanoparticles synthesized via sol-gel have found applications in catalysis, magnetic resonance imaging, and environmental remediation. For example, iron oxide nanoparticles prepared using the sol-gel method have demonstrated excellent adsorption capacity for various organic dyes, making them promising candidates for wastewater treatment (Niculescu et al., 2022). For instance, utilising Triton X-100 as a structural and pore-directing agent, magnetic SnO_2 nanoparticles made by the control sol–gel technique successfully underwent photodegradation of indigo carmine dye (AbouSeada et al., 2022).

Table 1: Different methods for synthesizing magnetic nanoparticles, their composites, and their respective advantages and disadvantages.

Method	Advantages	Disadvantages	References
Co-precipitation	1. Simple and cost-effective 2. Suitable for large-scale production 3. Aqueous synthesis at low temperatures	1. Limited control over size distribution 2. Potential for particle agglomeration 3. Oxidation of magnetite to maghemite	Ali et al., 2021
Thermal decomposition	1. Precise size and shape control 2. High crystallinity 3. Narrow size distribution	1. Requires high temperatures 2. Often uses toxic organic solvents 3. Limited scalability	Ali et al., 2021
Hydrothermal synthesis	1. Good control over particle size and shape 2. High purity and crystallinity 3. Environmentally friendly	1. Requires specialized equipment (autoclaves) 2. Long reaction times 3. Limited batch size	Dudchenko et al., 2022
Microemulsion	1. Good control over particle size 2. Uniform particle morphology 3. Suitable for coating particles	1. Low yield 2. Requires large amounts of surfactants 3. Difficult to scale up	Ali et al., 2021
Sol-gel method	1. Good control over composition 2. Allows for doping and functionalization 3. Low-temperature synthesis	1. Long processing times 2. Potential contamination from byproducts 3. Expensive precursors	Ali et al., 2021; Dudchenko et al., 2022
Sonochemical synthesis	1. Rapid reaction rates 2. Uniform size distribution 3. Prevents particle agglomeration	1. Specialized equipment required 2. Limited control over particle morphology 3. Potential for contamination from probe erosion	Dudchenko et al., 2022
Microwave-assisted synthesis	1. Rapid and energy-efficient 2. Uniform heating 3. Good control over particle size	1. Potential for hotspots and thermal runaway 2. Limited penetration depth in larger volumes 3. Specialized equipment needed	Donga et al., 2024
Biological synthesis	1. Environmentally friendly 2. Often room temperature synthesis 3. Potential for unique morphologies	1. Limited control over size and shape 2. Low yield 3. Purification challenges	Ali et al., 2021; Stiufiuc and Stiufiuc, 2024
Laser pyrolysis	1. Rapid synthesis 2. High purity products 3. Good control over particle size	1. Expensive equipment 2. Limited scalability 3. Potential for particle agglomeration	Majidi et al., 2016
Electrochemical synthesis	1. Good control over particle size 2. Room temperature synthesis 3. Avoids contamination from precursors	1. Limited to conductive substrates 2. Potential for impurities from electrodes 3. Challenging to scale up	Dudchenko et al., 2022
Ball milling	1. Simple, scalable 2. No solvents required	1. Irregular shapes 2. Contamination from grinding media	Stiufiuc and Stiufiuc, 2024

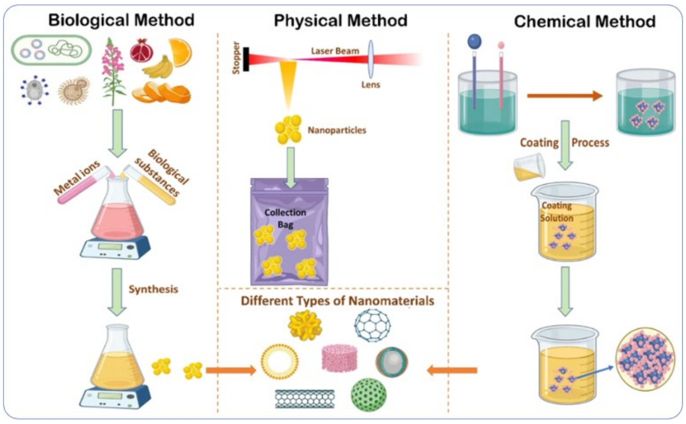

Fig. 2: Physical, chemical and biological methods for the synthesis of different types of MNPs (Shukla et al.,2021).

Hydrothermal synthesis is a powerful method for producing magnetic nanoparticles with high crystallinity and unique morphologies. This technique involves the crystallization of substances from high-temperature aqueous solutions at high vapor pressures. The hydrothermal approach allows for the synthesis of a wide range of magnetic nanoparticles, including complex metal oxides and ferrites. By adjusting reaction parameters such as temperature, pressure, and precursor concentrations, researchers can control the resulting nanoparticles' size, shape, and magnetic properties (Wei et al., 2012). $Co_xNi_{1-x}Fe_2O_4$ nanoparticles were created by Chen et al. utilising an intuitive and remarkably effective hydrothermal method without the need for a template or surfactant. They were then employed as an adsorbent to remove Congo red dye (Chen et al., 2014).

In recent years, biological methods for synthesizing magnetic nanoparticles have gained attention due to their eco-friendly nature and potential for large-scale production. These approaches utilize living organisms, such as bacteria, fungi, or plants, to produce magnetic nanoparticles. For instance, magnetotactic bacteria naturally produce magnetite nanoparticles with high purity and uniform size distribution. Authors Eshghi and Kashi, synthesised magnetic iron oxide nanoparticles (FeNPs/Ca-Alg beads) from bacteria and used them for the biodegradation of Acid Red 88 dye (Eshghi and Jookar Kashi, 2022). Plant-mediated synthesis, using extracts from various plant parts, has also emerged as a promising green method for producing magnetic nanoparticles. Akhtar et al. converted graphene oxide (GO) into reduced graphene oxide (rGO) by using *Azadirachta indica* leaf extract as an environmentally friendly reducing agent. Then, utilising the green deposition technique and leaf extract from *Azadirachta indica*, a nanocomposite of reduced graphene oxide and magnetite iron oxides, or FeNPs/rGO, was made and applied to the degradation of methylene blue (Akhtar et al., 2024). These biologically synthesized nanoparticles often exhibit enhanced biocompatibility and stability, making them attractive for biomedical applications. Additionally, some biogenic magnetic nanoparticles have demonstrated efficacy in the removal of organic dyes from aqueous solutions, highlighting their potential for environmental remediation (Ahmadi et al., 2021).

In conclusion, the synthesis of MNPs represents a dynamic and rapidly evolving field with far-reaching implications across multiple disciplines. The diverse array of synthesis methods available, including co-precipitation, thermal decomposition, sol-gel, hydrothermal, and biological approaches, offers researchers unprecedented control over the properties and characteristics of these remarkable materials. Each synthesis technique presents its own set of advantages and challenges:

a. Co-precipitation stands out for its simplicity and cost-effectiveness, making it ideal for large-scale production.
b. Thermal decomposition excels in producing highly monodisperse particles with excellent crystallinity, crucial for biomedical applications.
c. The sol-gel method offers versatility and the ability to create nanoparticles with controlled composition and structure.
d. Hydrothermal synthesis enables the production of highly crystalline particles with unique morphologies.
e. Biological methods provide eco-friendly alternatives with enhanced biocompatibility.

The ability to fine-tune the size, shape, composition, and magnetic properties of MNPs through these various synthesis methods has opened up a wide range of applications, from environmental remediation and wastewater treatment perspective. As research in this field continues to advance, one can anticipate the development of even more sophisticated synthesis techniques and novel applications for magnetic nanoparticles. The ongoing exploration of these materials promises to drive innovation in nanotechnology, materials science, and environmental engineering, potentially leading to groundbreaking solutions for some of the most pressing challenges facing our society today. The future of magnetic nanoparticle synthesis lies in the convergence of these various methods, potentially combining the strengths of different approaches to create hybrid techniques that offer even greater control over nanoparticle properties.

3. Nanomaterials for dye removal

3.1 Magnetic nanoparticles

Recent advances in nanoparticle technology have demonstrated significant potential for addressing textile wastewater contamination through innovative adsorption and degradation mechanisms. Multiple research teams have explored iron-based nanomaterials' capabilities in removing synthetic dyes and organic pollutants, developing optimized systems that combine high efficiency with environmental sustainability. These studies collectively highlight the versatility of magnetic nanoparticles in water treatment applications while advancing our understanding of contaminant removal processes across different operational conditions. Table 2 displays a comparative assessment of magnetic nanoparticles for dye removal.

Iron oxide nanoparticles have shown exceptional performance in dye removal applications across various experimental setups. Ali et al. (2024) demonstrated that Fe_3O_4 nanoparticles achieved 99.99% elimination of Acid Yellow 23 dye under optimized acidic conditions (pH 2) through monolayer adsorption mechanisms described by the Langmuir isotherm (Ali et al., 2024). Similarly, Balci et al. (2023) developed a magnetite/activated sludge hybrid system that enhanced Reactive Red 195 removal to 99.5% compared to 76.1% using biological treatment alone, while simultaneously reducing chemical oxygen demand by 94.32% through combined adsorption and biodegradation processes. The magnetic properties of these nanoparticles enable efficient recovery and reuse, particularly evident in systems using superparamagnetic Fe_3O_4 particles that maintain stability through multiple treatment cycles (Balci et al., 2023). Synthesis methods significantly influence nanoparticle performance and application potential. Yakar et al. (2020) produced 10–15 nm Fe_3O_4 particles through co-precipitation, demonstrating temperature-dependent adsorption behavior that shifts from monolayer to multilayer mechanisms (Yakar et al., 2020). Environmentally friendly approaches have emerged as viable alternatives, with Bibi et al. (2019) successfully synthesizing Fe_2O_3 nanoparticles using pomegranate seed extract, achieving 95.08% photocatalytic degradation of reactive blue 4 under UV light (Bibi et al., 2019). Giri et al. (2011) advanced sustainable material science by repurposing iron ore tailings into functional magnetic nanoparticles with adsorption capacities comparable to those synthesized from pure reagents. MNPs were found to be effective in the quick adsorptive removal of methylene blue and congo red dyes from water solutions. The highest monolayer adsorption efficiencies for methylene blue and Congo red under ideal conditions were determined to be 70.4 mg g^{-1} and 172.4 mg g^{-1}, respectively (Giri et al., 2011).

Operational parameters and system design critically determine treatment efficiency. Thabet et al. (2021) identified dye concentration and pH as key factors through response surface methodology, achieving complete color removal at 100 ppm concentrations despite unusual exothermic reaction characteristics (Thabet et al., 2023). Practical applications show promise, with Hamdy et al. (2018) reporting 97.2% methylene blue removal using nano zero-valent iron while simultaneously reducing multiple contaminants in real textile effluents at operational costs of $1.66/$m^3$ (Hamdy et al., 2018). Samrot et al. (2021) optimized crystal violet removal to 94.7% using SPIONs-a nanoparticles under alkaline conditions, demonstrating the importance of surface charge and particle size in adsorption processes (Samrot et al., 2021).

The collective findings from these studies establish iron-based nanoparticles as multifunctional tools for water remediation, combining high contaminant removal efficiency with magnetic separability and environmental compatibility. From chemically synthesized magnetite to biologically produced iron oxides and repurposed industrial byproducts, the developed systems address both technical and ecological challenges in wastewater treatment. Future developments could focus on scaling these laboratory successes into industrial applications while further optimizing nanoparticle recovery and reuse cycles to enhance economic viability across different treatment scenarios.

Table 2: Comparative analysis of magnetic nanoparticles synthesized using different methods for dye removal.

MNPs	Synthesis method	Dye	Removal method	Catalyst	Kinetics	Isotherm	Removal efficiency (%)/Adsorption capacity (mg g^{-1})	References
Fe_3O_4	-	Acid Yellow 23	Adsorption	-	Pseudo-first order	Langmuir	0.47 mg g^{-1}	Ali et al., 2024
Fe_3O_4	Co-precipitation	Reactive Red 195	Adsorption	-	-	Freundlich	76.10%	Balci et al., 2023
Fe_3O_4	Co-precipitation	(Maxilon® Blue GRL	Adsorption	-	Pseudo-second order	Langmuir and Freundlich isotherm	0.24 mg g^{-1}	Yakar et al., 2020
Fe_2O_3	Hydrothermal	Procion blue dye	Degradation	Sunlight	-	-	80%	Parvin et al., 2018
Fe_2O_3	Co-precipitation	Reactive blue	Degradation	UV light	-	-	95.08%	Bibi et al., 2019
Fe_3O_4	Co-precipitation	Levafix Blue CA	Degradation	AOP (·OH radicals)	Pseudo-second order	-	99%	Thabet et al., 2021
nZVI	Liquid phase reduction	Methylene blue	Degradation	AOP (·OH radicals)	-	Langmuir and Freundlich	72.1%	Hamdy et al., 2018
γ-Fe_2O_3	Co-precipitation	Congo red	Adsorption	-	-	Langmuir and Freundlich	208.33 mg g^{-1}	Afkhami and Moosavi, 2010
Superparamagnetic Iron Oxide Nanoparticles (SPIONs)	Co-precipitation	Crystal violet	Adsorption	-	-	Langmuir and Freundlich	94.7%	Samrot et al., 2021
Fe_3O_4	Co-precipitation	Methylene blue	Adsorption	-	-	Langmuir	70.4 mg g^{-1}	Giri et al., 2011

3.2 Magnetic nanoparticle composites

A complex class of adsorbents, magnetic nanoparticle composite materials integrate the functional characteristics of other materials with the magnetic properties of MNPs. A nanocomposite is a multiphase solid material with dimensions smaller than 100 nm (Nithya et al., 2021). These composites usually have a magnetic core that has been coated or merged with carbon-based materials, organic polymers, or other essential elements. When contrasted with raw MNPs, the combinatorial impact of these mixtures frequently leads to improved adsorption capacity, selectivity, and stability. Carbon-based materials such as graphene oxide can greatly enhance the surface area accessible for adsorption, while the addition of polymers can enhance the dispersion and chemical stability of MNPs (Jain, 2022). Fig. 3 represents MNPs and their composite materials application in dye adsorption and degradation. Table 3 shows a comparative analysis of composite magnetic nanoparticles for dye removal. Table 4 represents a comparative table of magnetic nanoparticles and their composite materials, highlighting their advantages and disadvantages.

The development of ecologically safe and more effective magnetic nanocomposites for the elimination of textile dyes has been the main thrust of current developments in the area of study. The composite resolved important issues in real-world applications with its great reusability and quick magnetic separation. These environmentally friendly materials have the extra benefit of being readily regenerative and reusable, and they demonstrate exceptional efficacy in eliminating both cationic and anionic dyes from textile effluent. In the adsorption method for the water purification process, magnetic composites have found extensive application. The primary benefit of magnetic composites is their ability to rid of large amounts of wastewater quickly and without producing any pollutants. The majority of magnetic particles that are sold commercially are relatively costly and unsuitable for use in large-scale operations. Low-cost adsorbents may be magnetically modified to provide materials for environmental and biotechnological use. A potential route for simple separation is offered by magnetic separation, in which particles that have a strong attraction for the target species combine with the heterogeneous solution. The particles tag the target pollutant when they combine with the solution. The tagged contaminant is subsequently extracted from the solution using an external magnetic field. The maximal adsorption and degradation capacity of magnetic composites and models that fit a variety of dyes is shown in Table 3 (Sivashankar et al., 2014).

In a notable study, Gautam and Tiwari developed an innovative approach to water purification by synthesizing humic acid-functionalized Fe_3O_4 nano-sorbents (Fe_3O_4/HA) through an environmentally benign process. These nano-sorbents demonstrated remarkable efficacy in the decolorization of malachite green, a known carcinogenic dye, from aqueous solutions. The adsorption kinetics of this process adhered to a pseudo-second-order model, indicative of chemisorption mechanisms. Concurrently, the adsorption isotherm revealed multilayer adsorption characteristics, suggesting a complex interaction between the adsorbate and the nanocomposite surface. The researchers further explored the synergistic effect of ultrasonic waves on the decolorization process. Ultrasonic irradiation is attributed to the generation of highly reactive hydroxyl radicals (OH^-) in the solution. These radicals rapidly interact with malachite green molecules, facilitating their degradation and subsequent removal from the aqueous environment. A key advantage of the Fe_3O_4/HA nano-sorbents lies in their recyclability, which is crucial for sustainable water treatment applications. The used nano-sorbents can be effectively regenerated using a 0.1 M HCl solution, allowing for their reuse in multiple adsorption-desorption cycles. Experimental data demonstrated that these nanocomposites maintain their efficacy for up to five consecutive cycles, highlighting their potential for long-term use in water purification systems (Gautam and Tiwari, 2020).

MNPs were successfully synthesized using an environmentally friendly approach employing *Parkia speciosa* Hassk pod extract. The resulting MNPs exhibited a predominantly spherical morphology with particle dimensions ranging from 10 to 80 nm. X-ray diffraction analysis revealed that the nanocomposite material comprised a mixture of iron oxide phases, specifically Fe_2O_3 and Fe_3O_4. These MNPs demonstrated both magnetic properties and photocatalytic activity, particularly in the degradation of bromophenol blue (BPB). The photocatalytic performance of the synthesized MNPs was evaluated under various conditions to elucidate the factors influencing the degradation process. The addition of hydrogen peroxide (H_2O_2) as an oxidizing agent significantly enhanced the reaction kinetics and overall degradation efficiency. Moreover, the light source played a crucial role in the photocatalytic activity, with ultraviolet (UV) irradiation facilitating more rapid degradation compared to visible light. These observations suggest a synergistic effect between the MNPs, H_2O_2, and incident radiation in the photocatalytic system. The proposed mechanism for BPB degradation primarily involved the generation of hydroxyl radicals (OH^-), which act as powerful oxidants in the photocatalytic process. An essential aspect of the developed MNP-based photocatalytic system is its reusability, a critical factor for practical applications and cost-effectiveness. The stability and catalytic activity of the MNPs were assessed through multiple degradation cycles. Kinetic analysis revealed insignificant changes in the reaction rates between the first and third cycles, indicating excellent reusability of the magnetic nanocomposite (Fatimah et al., 2020).

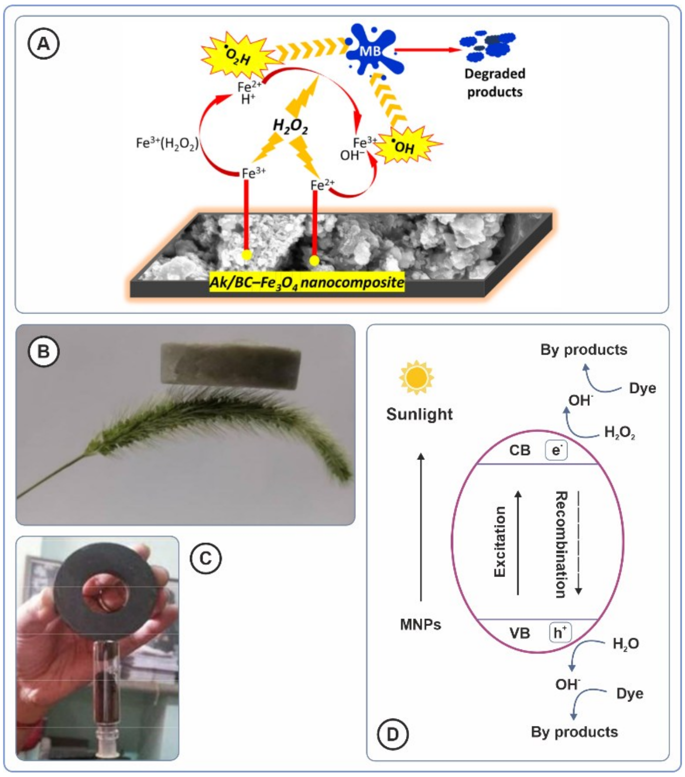

Fig. 3: MNPs and their composite materials and application in dye adsorption and degradation, (A) Fenton-like degradation of MB dye by Ak/BC–Fe_3O_4 nanocomposite (Vinayagam et al., 2024), (B) A magnetic aerogel kept on a green bristlegrass (Wang et al., 2021), (C) Fe_3O_4/HA composite material (Gautam and Tiwari, 2020), and (D) Basic dye degradation mechanism in the photocatalysis.

In a study, a novel adsorbent was synthesized by incorporating cellulose with polyethyleneimine (PEI) and magnetic nanoparticles (MNPs) through a crosslinking method, utilizing glutaraldehyde (GTA) as the crosslinking agent. The optimization process revealed that the most effective composition was achieved with a 2:1 mass-to-volume ratio of cellulose to PEI, an impregnation duration of 6 hours, a crosslinking period of 60 minutes, a GTA concentration of 1% v/v, and an MNP mass of 0.6 g. The resulting magnetic cellulose-PEI composite (MCPEI) exhibited ferromagnetic properties, making it suitable for magnetic separation applications. The adsorption kinetics of the MCPEI were best described by the pseudo-second-order model, indicating that chemisorption was the predominant mechanism in the dye removal process. Isotherm studies revealed that the experimental data aligned well with the Langmuir model, suggesting monolayer adsorption on the adsorbent surface. The MCPEI demonstrated remarkable reusability, maintaining sufficient magnetic sensitivity after five consecutive adsorption-desorption cycles. This property allows for efficient recovery of the adsorbent from aqueous solutions using an external magnetic field, facilitating its regeneration and reuse. The regeneration process was found to be more effective when using hydrochloric acid compared to distilled water. The regenerated adsorbent exhibited a notably high adsorption efficiency of 74.9%, underscoring its potential for sustainable and cost-effective water treatment applications (Nordin et al., 2021).

A promising solution in this field involved the utilization of *Acacia koa* pod covers, a readily available and carbon-rich green resource, for the facile synthesis of an Ak/BC–Fe_3O_4 nanocomposite. This innovative material has demonstrated remarkable efficacy in the Fenton-like degradation of methylene blue (MB) dye, a common water pollutant. Advanced characterization techniques have revealed the nanocomposite's exceptional properties, including a high surface area of 7.11 $m^2\ g^{-1}$, a mesoporous architecture with an average pore size of 22.06 nm, and superparamagnetic behavior with a saturation magnetization of 8.64 emu g^{-1}. These characteristics contribute to its superior performance in dye degradation processes. In Fenton-like reactions, the Ak/BC–Fe_3O_4 nanocomposite exhibited stellar performance, achieving 96% MB degradation within 180 minutes. Kinetic modelling of the degradation process demonstrated that it follows a first-order model, indicating a consistent rate of dye removal throughout the treatment. The proposed mechanism for MB degradation involves the generation of highly reactive hydroxyl (HO^-) and hydroperoxyl (HO_2^-) radicals through the interaction of Fe^{2+} and Fe^{3+} ions with hydrogen peroxide (H_2O_2). The sequence of reactions in this Fenton-like process can be described as follows:

Fe^{2+} (from nanocomposite) + $H_2O_2 \rightarrow Fe^{3+} + OH^- + HO\bullet$

Fe^{3+} (from nanocomposite) + $H_2O_2 \rightarrow Fe^{3+} (H_2O_2)$

$Fe^{3+} (H_2O_2) \rightarrow Fe^{2+} + H^+ + HO_2\bullet$

MB dye + $HO\bullet + HO_2\bullet \rightarrow CO_2 + H_2O$ + harmless components

The practical applicability of the Ak/BC–Fe_3O_4 nanocomposite is further enhanced by its remarkable stability and reusability. Recycling studies have demonstrated that the nanocomposite maintains its catalytic activity for up to seven consecutive cycles, with degradation efficiency ranging between 85% and 90%. This high degree of stability not only increases the economic viability of the process but also aligns with principles of sustainable materials use in environmental remediation (Vinayagam et al., 2024).

Magnetic activated carbon (MAC) composites have emerged as promising materials for water treatment applications, particularly in the removal of dyes. A recent study investigated a novel MAC with a moderate specific surface area of 264.97 $m^2\ g^{-1}$ and notable magnetic properties, exhibiting a saturation magnetization of 3.77 emu g^{-1}. This MAC was synthesized through an innovative one-step pyrolysis method, utilizing oak pericarp pretreated with $FeCl_3$ and $ZnCl_2$. The resulting composite demonstrated remarkable efficacy in the adsorption of two model dyes: rhodamine B and rose bengal. For rhodamine B, maximum adsorption was achieved at pH 2, with the process reaching equilibrium in 180 minutes. The monolayer adsorption capacity for rhodamine B was determined to be 198.52 mg g^{-1}, indicating a high affinity of the MAC for this particular dye. In contrast, rose bengal adsorption exhibited optimal performance at neutral pH, with a shorter equilibrium time of 120 minutes and a monolayer adsorption capacity of 42.55 mg g^{-1}. The pseudo-second-order kinetic model best described the adsorption process for both rhodamine B and rose bengal, suggesting that chemisorption might be the rate-limiting step. The Freundlich isotherm model showed the best fit for both dyes, indicating a heterogeneous adsorption process with multilayer coverage. Thermodynamic analysis revealed that the adsorption processes for both dyes were endothermic and spontaneous in nature. This characteristic suggests that the MAC's adsorption capacity may improve at elevated temperatures, potentially expanding its applicability in various industrial settings. Furthermore, desorption studies demonstrated the regenerative potential of the MAC, maintaining its efficacy through four consecutive adsorption-desorption cycles (Saadi et al., 2024).

Table 3: Comparative analysis of composite magnetic nanoparticles for dye removal.

Composite MNPs	Synthesis method	Dye	Removal method	Catalyst	Mechanism	Removal efficiency (%)/Adsorption capacity (mg g^{-1})	Eluent	Reusability	References
Fe_3O_4/HA	Co-precipitation	Malachite green	Synchronous adsorption and degradation	Ultrasonication	Chemisorption, multilayer adsorption with ROS production (•OH)	97	HCl	Up to five cycles for 85% removal	Gautam and Tiwari (2020)
Parkia speciosa Hassk pod-Fe_3O_4-Fe_2O_3	Reduction reaction	Bromophenol blue	Degradation	H_2O_2 + Photocatalysis (UV light)	ROS production (•OH)	98	UV and visible light	Up to three cycles for 95% removal	Fatimah et al. (2020)
MCPEI (Polyethyleneimine and magnetic nanoparticle)	Crosslinking	Black 5	Adsorption	-	Chemisorption with monolayer adsorption	99	Distilled water	Up to five cycles for 48% removal	Nordin et al. (2021)
Ak/BC-Fe_3O_4	Hydrothermal reaction	Methylene blue	Degradation	H_2O_2 + Fenton-like degradation	Physisorption with ROS production (OH^- and •OH)	96	-	Up to seven cycles for 90% removal	Vinayagam et al., 2024
MAC (Magnetic activated carbon)	Co-precipitation	Rhodamine B and Rose Bengal	Adsorption	-	Chemisorption with monolayer adsorption			Up to four cycles for o 67% removal	Saadi et al., 2024
BCA/Fe_3O_4-NPs Membrane	-	Congo Red and Acid Orange.	Adsorption	-	Dipole-dipole interaction	8.95 and 4.44 mg g^{-1}	-	-	Suryanto et al., 2024
(MgCF)@SiO_2-NH-COOH	Co-precipitation	Methylene blue and Rhodamine B	Adsorption and degradation	-	Monolayer adsorption	98.6 for MB and 95.3 RhB	Distilled water with pH 11.	Up to five cycles, for 82.5 % MB and 79.6 % RhB removal	Salih et al., 2024
Graphene oxide/activated kaolin/magnetite (rGO/AK/Fe_3O_4)	Co-precipitation	Methylene blue	Adsorption	-	Chemisorption with monolayer adsorption	98.2	-	Up to five cycles for 98% removal	Ahmed et al., 2025
Fe_3O_4@APS@AA-co-CA	Co-precipitation	Crystal violet	Adsorption	-	Chemisorption with monolayer adsorption	208.3 mg g^{-1}	HCl (pH 1)	Up to four cycles for 63% removal	Ge et al., 2012
MNZnFe	Microwave assisted hydrothermal method	Acid red 88	Adsorption	-	Chemisorption with monolayer adsorption	111.1 mg g^{-1}	Methanol	Single cycle with 81% removal	Konicki et al., 2013
Magnetic Graphene Oxide (Fe_3O_4-GO)	In-situ precipitation	Rhodamine B	Adsorption	-	Chemisorption with monolayer adsorption	99.12	Ethanol	Up to seven cycles for 58% removal	Donga et al., 2024
Fe_3O_4@SiO_2-NH_2-Asn	Co-precipitation	Carmoisine	Adsorption	-	Chemisorption with multilayer adsorption	96.6	NaOH (0.1 mol L^{-1})	Up to seven cycles for 79% removal	Mostashari et al., 2021
MOF@Fe_3O_4@activated carbon	Co-precipitation	Indigo carmine	Adsorption	-	Physicochemical adsorption	99.5	Methanol	Up to four cycles for 86% removal	Paz et al., 2021
$MgFe_2O_4$/rGO	Sonication	Methylene blue	Adsorption	-	Chemisorption with multilayer adsorption	24.81 mg g^{-1}	NaOH (0.001 M)	Up to four cycles for 75% removal	Adel et al., 2021
Magnetic aerogel	Co-precipitation	Methylene blue	Adsorption	-	-	97.5	-	-	Wang et al., 2021

Recent advancements in the development of magnetic nanocomposite membranes have shown promising results for wastewater treatment applications. A novel approach utilizing pineapple biowaste extract to synthesize bacterial cellulose acetate (BCA) membranes functionalized with Fe_3O_4 nanoparticles (NPs) has been successfully investigated. This innovative method not only addresses the issue of biowaste management but also creates a value-added product with potential environmental remediation applications. Microscopic examination of the membrane surface revealed a tendency for Fe_3O_4-NPs to form clusters, which can significantly influence the membrane's properties and performance. The incorporation of Fe_3O_4-NPs into the BCA membrane matrix induced a remarkable transformation in magnetic properties, transitioning from a non-magnetic membrane to one exhibiting paramagnetic characteristics. This magnetic behavior enhancement opens up new possibilities for membrane manipulation and recovery in water treatment processes. The mechanical properties of the nanocomposite membranes were found to be significantly improved by the addition of Fe_3O_4-NPs. Notably, the incorporation of Fe_3O_4-NPs at a concentration of 0.75 wt % resulted in a substantial increase in tensile strength, reaching 67.09 ± 4.68 MPa. This represents a 37% improvement compared to the unmodified BCA membrane, indicating enhanced durability and potential for extended operational lifetimes in filtration applications (Suryanto et al., 2024).

In a study, a novel magnetic nanocomposite was synthesized and evaluated for its efficacy in dyed water treatment. The core of the composite consisted of magnesium-doped $CoFe_2O_4$ nanoparticles, fabricated via a co-precipitation method. These nanoparticles were subsequently encapsulated in a silica shell matrix and functionalized with amino groups through the application of 3-Aminopropylethoxysilane (APTES). A key innovation in this research was the strategic incorporation of Gallic acid (GA) to enhance the adsorption capabilities of the composite. The resulting MgCF-SiO_2-APTES-GA nanocomposite exhibited remarkable potential as a high-performance magnetic nano-adsorbent. This was evidenced by its exceptional adsorption capacity for two common dyes: methylene blue and rhodamine B. Kinetic analyses revealed that the adsorption process adhered to the Boyd kinetic model, while equilibrium data were best described by the Langmuir isotherm model. A quantitative assessment of the nanocomposite's adsorption performance yielded impressive results. Maximum adsorption capacities of 103 mg g^{-1} and 89 mg g^{-1} were observed for MB and RhB, respectively. These values underscore the nanocomposite's high affinity for these dyes and its potential for efficient water purification applications. Furthermore, the MgCF-SiO_2-APTES-GA nanocomposite demonstrated excellent recyclability, maintaining its adsorption-desorption efficacy over five consecutive cycles (Salih et al., 2024).

A novel rGO/AK/Fe_3O_4 nanocomposite, synthesized using simple methods, has shown remarkable efficiency in removing methylene blue (MB) from aqueous solutions. This composite, derived from spent batteries and clay, addresses disposal issues while maximizing the utilization of natural resources. Under optimized conditions, including pH 10, an adsorbent dose of 50 mg, and an initial MB concentration of 15 mgL^{-1}, the nanocomposite achieved a maximum removal efficiency of 98.2% within 12 minutes. The adsorption process followed the Langmuir isotherm model, indicating homogeneous monolayer adsorption with a maximum capacity of 35.93 mg g^{-1}. Kinetic studies revealed that the pseudo-second-order model best described the adsorption process, while thermodynamic parameters suggested an exothermic and spontaneous nature of the adsorption (Ahmed et al., 2025).

Another innovative approach involved the synthesis of magnetic $ZnFe_2O_4$ adsorbent via a microwave-assisted hydrothermal method for acid dye removal. This adsorbent exhibited optimal performance at low pH, with a maximum monolayer adsorption capacity of 111.1 mg g^{-1} for Acid Red 88 (AR88). The adsorption kinetics aligned with the pseudo-second-order model, and equilibrium data fit well with the Langmuir isotherm. Thermodynamic analysis indicated that the adsorption of AR88 onto $ZnFe_2O_4$ was spontaneous and exothermic (Konicki et al., 2013). Fe_3O_4-GO nanocomposite, synthesized through an environmentally friendly in-situ precipitation method, demonstrated excellent adsorption capabilities for cationic Rhodamine B (RhB) dye. The composite exhibited a saturation magnetization of 34 emu/g, allowing for facile magnetic separation from aqueous solutions. X-ray photoelectron spectroscopy (XPS) confirmed the chemical composition of the nanocomposite, while Brunauer-Emmett-Teller (BET) analysis revealed surface areas of 61.34 m^2 g^{-1} for Fe_3O_4-GO. The adsorption process followed the Langmuir isotherm model, with a maximum monolayer adsorption capacity of 70.64 mg/g at room temperature. Kinetic studies showed that the pseudo-second-order model best described the adsorption process, with the composite maintaining stability for up to 7 adsorption-desorption cycles (Donga et al., 2024).

Table 4: Comparative table of magnetic nanoparticles and their composite materials, highlighting their advantages and disadvantages.

Material	Advantages	Disadvantages	References
Magnetic Nanoparticles (MNPs)	1. High chemical stability 2. Narrow size distribution 3. Superparamagnetic properties 4. Tunable magnetic moment 5. Potential for functionalization	1. Pyrophoric nature 2. Reactivity to oxidizing agents 3. Tendency to agglomerate 4. Handling challenges	Lu et al., 2021
Magnetic Nanoparticle Composites (Various mixtures of MNPs)	1. Enhanced stability 2. Improved biocompatibility 3. Multifunctionality 4. Tailored applications 5. Potential for drug delivery	1. Reduced magnetic response 2. Complexity in synthesis 3. Potential instability in certain environments	Picchi et al., 2024; Lu et al., 2021; Govan, 2020
Polymer-Magnetic Nanocomposites	1. Improved dispersion stability 2. Enhanced mechanical properties 3. Controllable magnetic properties 4. Potential for stimuli-responsive behavior	1. Reduced saturation magnetization 2. Challenges in uniform particle distribution 3. Potential polymer degradation over time	Gradinaru et al., 2021; Bustamante-Torres et al., 2022

Carbon-Coated Magnetic Nanoparticles	1. Higher chemical stability 2. Resistance to acidic/basic conditions 3. Potential for functionalization 4. Enhanced thermal stability	1. Complex synthesis process 2. Potential reduction in magnetic properties 3. Higher production costs	Mourdikoudis et al., 2021
Silica-Coated Magnetic Nanoparticles	1. Improved colloidal stability 2. Easy surface modification 3. Enhanced biocompatibility 4. Protection against aggregation	1. Potential reduction in magnetic response 2. Challenges in controlling shell thickness 3. Possible silica degradation in certain conditions	Hauser et al., 2015

These MNPs achieved a remarkable removal efficiency of ~96.6% under optimized conditions of pH 3 and 0.08 g adsorbent dosage within 20 minutes. The adsorption process followed the Freundlich isotherm model and exhibited pseudo-second-order kinetics, indicating chemisorption. The adsorbent demonstrated excellent reusability, with only a minor decrease in efficiency after seven cycles, highlighting its economic viability for large-scale applications (Mostashari et al., 2021). A magnetic MOF@Fe_3O_4@AC composite has been developed for the efficient removal of indigo carmine dye. This composite exhibited superior adsorption efficiency compared to its constituents, achieving 98-99% dye removal at neutral pH. The adsorption process aligned with the Temkin and Langmuir isotherm models, while kinetic data fit the Elovich model. Thermodynamic analysis revealed a spontaneous and endothermic process with increased entropy. The adsorbent maintained an 86% removal capacity even after four cycles, demonstrating its potential for practical wastewater treatment applications (Paz et al., 2021). $MgFe_2O_4$/rGO nanoparticles have shown promise in removing methylene blue (MB) dye from aqueous solutions. The strong electrostatic attraction between $MgFe_2O_4$ and reduced graphene oxide (rGO) facilitates the dispersion of magnesium ferrite on the wrinkled sections of rGO sheets, enhancing the magnetic properties of the composite. The adsorption mechanism followed the Freundlich model, indicating a heterogeneous surface and multilayer formation. Kinetic studies revealed a pseudo-second-order mechanism, and the adsorbent demonstrated high stability and reusability over four cycles (Adel et al., 2021).

Recent innovations have led to the development of magnetic aerogels as highly efficient and easily collectible adsorbents for dye removal. These aerogels, prepared from cross-linked sodium carboxymethylcellulose and incorporating magnetic Fe_3O_4 nanoparticles, exhibited low density and a porous structure. With a removal rate of 97.5% for methylene blue in 6 hours and a maximum adsorption capacity of 83.6 mg g^{-1}, these aerogels demonstrate excellent potential for water treatment applications. Their magnetic properties enable easy collection and reuse, ensuring long-term integrity and floatability in aqueous environments (Wang et al., 2021).

In conclusion, the field of magnetic material composites for dyed water treatment has witnessed significant advancements in recent years. These innovations have led to the development of highly efficient, environmentally friendly, and reusable adsorbents capable of addressing the complex challenges posed by textile effluents and other dye-contaminated wastewater. The integration of magnetic properties with various functional materials has resulted in nanocomposites that exhibit enhanced adsorption capacities, improved selectivity, and facile separation from treated water. The diverse range of synthesis methods, from green approaches utilizing plant extracts to more sophisticated chemical processes, has expanded the toolkit available to researchers and practitioners in water treatment.

The observed adsorption mechanisms, predominantly following pseudo-second-order kinetics and often aligning with Langmuir or Freundlich isotherm models, provide valuable insights into the nature of dye-adsorbent interactions. This understanding is crucial for optimizing treatment processes and designing more effective composites. Moreover, the demonstrated reusability of many of these magnetic nanocomposites, often maintaining high efficiency over multiple adsorption-desorption cycles, addresses critical concerns regarding the economic viability and sustainability of water treatment technologies. As research in this field continues to evolve, future directions may include further exploration of synergistic effects between different components of magnetic composites, development of multi-functional materials capable of addressing a broader spectrum of water pollutants and scaling up of promising technologies for industrial applications. The integration of advanced characterization techniques and computational modelling may also play a crucial role in fine-tuning the properties of these materials for specific environmental remediation tasks.

The progress made in magnetic material composites for dyed water treatment not only contributes to addressing immediate environmental concerns but also paves the way for more comprehensive and sustainable approaches to water purification. As global water scarcity and pollution issues become increasingly pressing, these innovative materials stand at the forefront of technological solutions, offering hope for more efficient and environmentally friendly water treatment processes in the future.

4. Limitations of MNPs and their composite materials

Magnetic nanoparticles (MNPs) and their composites have garnered significant attention in various fields, including environmental remediation. However, despite their promising properties, these materials face several limitations that hinder their widespread adoption and efficacy. This comprehensive analysis explores the key limitations of magnetic nanoparticles and their composites, with a focus on their applications in dye removal from the environment.

4.1. Stability and Agglomeration Issues

One of the primary challenges associated with magnetic nanoparticles is their tendency to agglomerate due to strong magnetic interactions and high surface energy (Rarokar et al., 2024). This agglomeration can significantly reduce the effective surface area of the nanoparticles, thereby diminishing their adsorption capacity and overall performance in dye removal applications. The stability of MNPs in aqueous solutions is crucial for their effectiveness in environmental remediation. However, maintaining colloidal stability while preserving magnetic properties remains a significant challenge. The aggregation of nanoparticles not only reduces their active surface area but also alters their magnetic behavior, potentially leading to decreased efficiency in magnetic separation processes (Moosavi et al., 2020).

4.2.Biocompatibility and Toxicity Concerns

While iron oxide nanoparticles are generally considered biocompatible, concerns persist regarding their potential toxicity, especially when used in high concentrations or for prolonged periods (Moosavi et al., 2020). The small size of nanoparticles allows them to penetrate cellular membranes and potentially accumulate in various organs, raising concerns about their long-term effects on human health and ecosystems. Recent studies have shown that the toxicity of MNPs is influenced by various factors, including particle size, surface coating, and dose (Nowak-Jary and Machnicka, 2024). For instance, smaller nanoparticles (5-10 nm) have been found to exhibit higher cytotoxicity compared to larger ones (30 nm) in certain cell lines. This size-dependent toxicity poses challenges in designing MNPs for environmental applications, as smaller particles are often preferred for their higher surface area and enhanced adsorption properties (Kazemi et al., 2023).

4.3.Limited Magnetic Saturation and Low Efficiency

Despite their magnetic properties, some MNPs exhibit limited magnetic saturation, which can affect their performance in magnetic separation processes (Neamtu et al., 2018). This limitation is particularly seen in nanoparticles with smaller core sizes, which are often preferred for their higher surface area and improved adsorption capacity. The conflict between magnetic properties and adsorption efficiency presents a significant challenge in optimizing MNPs for dye removal applications. While smaller particles offer better adsorption, their magnetic response may be insufficient for effective separation, especially in complex environmental matrices.

4.4.Challenges in Large-Scale Synthesis and Reproducibility

The synthesis of magnetic nanoparticles with consistent properties at large scales remains a significant hurdle. Variations in particle size, shape, and surface properties can occur between batches, affecting the reproducibility of results in dye removal applications. This lack of consistency poses challenges for industrial-scale implementation of MNP-based water treatment technologies. Moreover, the cost-effectiveness of large-scale production is another limiting factor. While laboratory-scale synthesis methods have been well-established, scaling up these processes while maintaining the desired nanoparticle properties and keeping costs low is an ongoing challenge for researchers and industry professionals.

4.5.Environmental Impact and Long-Term Behavior

The long-term fate and behavior of magnetic nanoparticles in the environment are not fully understood (Ali et al., 2021). There are concerns about the potential accumulation of these materials in ecosystems and their interactions with various environmental components. The potential for MNPs to act as carriers for other pollutants or to undergo transformations that alter their properties over time adds another layer of complexity to their environmental impact assessment. Furthermore, the release of metal ions from MNPs, particularly under acidic conditions often encountered in wastewater treatment scenarios, raises concerns about secondary pollution and the long-term sustainability of MNP-based water treatment solutions. While ROS are effective in degrading pollutants, their non-selective nature can potentially harm beneficial microorganisms and aquatic life if released into natural water bodies. Excessive ROS generation could disrupt the delicate balance of aquatic ecosystems (Kolya and Kang, 2024).

4.6.Implications for Dye Removal Applications

The limitations of magnetic nanoparticles have significant implications for their application in dye removal from the environment. The agglomeration tendency of MNPs can lead to reduced adsorption capacity and difficulty in regenerating the adsorbent material, potentially increasing operational costs and decreasing the overall efficiency of the treatment process (Hong et al., 2024). The biocompatibility and toxicity concerns associated with MNPs necessitate careful consideration of their use in water treatment applications, especially in scenarios where treated water may come into contact with living organisms. This limitation may require additional treatment steps or the development of novel, less toxic nanocomposite materials for environmental remediation. The challenges in large-scale synthesis and reproducibility hinder the widespread adoption of MNP-based technologies in industrial wastewater treatment. Inconsistencies in nanoparticle properties can lead to variable treatment efficiencies, making it difficult to design and implement standardized treatment protocols.

4.7.Current Research and Future Directions

Recent research has focused on addressing these limitations through various strategies. For instance, surface modification techniques using biocompatible polymers or inorganic coatings have shown promise in improving the stability and reducing the toxicity of MNPs. The development of novel nanocomposite materials, combining MNPs with other adsorbents or catalysts, has also emerged as a potential solution to enhance both magnetic properties and adsorption efficiency (Wang et al., 2015). Advances in synthesis methods, such as microfluidic-assisted synthesis and controlled co-precipitation techniques, are being explored to improve the reproducibility and scalability of MNP production (Ali et al., 2021). These approaches aim to provide better control over particle size distribution and surface properties, addressing some of the key challenges in large-scale applications.

In conclusion, while magnetic nanoparticles and their composites offer promising solutions for environmental remediation, particularly in dye removal applications, several limitations need to be addressed to fully realize their potential. Ongoing research efforts focused on enhancing stability, reducing toxicity, improving magnetic properties, controlling ROS production and developing scalable synthesis methods are crucial for overcoming these challenges and advancing the field of MNP-based water treatment technologies.

5. Conclusion and future prospects

In conclusion, magnetic nanoparticles (MNPs) and their composites represent a transformative advancement in the field of water treatment, particularly for dye-contaminated wastewater. Their unique properties, such as high surface area, magnetic responsiveness, and catalytic capabilities, enable efficient adsorption and degradation of a wide range of dyes. Recent studies have demonstrated their potential to achieve remarkable removal efficiencies through mechanisms like adsorption, photocatalytic degradation, and Fenton-like reactions. Furthermore, advancements in synthesis methods ranging from co-precipitation to green biological approaches have enhanced the performance and environmental compatibility of these materials. The integration of MNPs into composite materials has further improved their stability, selectivity, and reusability, making them promising candidates for sustainable water purification technologies. Despite these advancements, challenges remain. Issues such as nanoparticle agglomeration, limited magnetic saturation, potential toxicity, and scalability hinder the widespread adoption of MNP-based technologies. Addressing these limitations requires continued innovation in surface modification techniques, synthesis methods, and the development of multifunctional composites. Additionally, understanding the long-term environmental impact and behavior of MNPs is essential for ensuring their safe application.

5.1.Future Directions:

- Research should focus on improving the colloidal stability of MNPs in aqueous environments through advanced surface coatings or functionalization techniques.
- Developing advanced greener synthesis approaches using plant extracts or biogenic methods can reduce environmental impact while maintaining nanoparticle efficacy.
- Efforts should prioritize scalable synthesis techniques that maintain consistency in nanoparticle properties while reducing production costs.
- Scaling up laboratory successes to industrial-scale applications will require pilot studies and optimization of operational parameters.
- Employing computational modelling and advanced characterization techniques can provide deeper insights into adsorption mechanisms and guide material design.
- Emphasis on reusability and regeneration cycles will enhance the economic viability and environmental sustainability of MNP-based systems.

By addressing these challenges and exploring these future directions, magnetic nanoparticles and their composite materials have the potential to revolutionize water treatment technologies, contributing significantly to global efforts in combating water pollution and ensuring environmental sustainability.

Declaration of interests/ Conflict of interest

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Data availability

Data will be made available on request

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