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A review on recent progress in supported magnetic nanoparticles: From synthetic methods to applications

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Abstract

Magnetic nanoparticles supported on various materials have recently gained significant attention due to their wide range of applications across multiple fields such as catalysis, biomedicine, environmental remediation, and magnetic separation. The support materials are essential for stabilizing magnetic nanoparticles and enhancing their properties, thereby improving their performance and versatility. This review presents a comprehensive summary of recent advancements and key developments in supported magnetic nanoparticles, focusing on various support materials including silica, alumina, cellulose, charcoal, polymeric materials, and carbon nanotubes. We also discussed why we needed a shift from conventional nanoparticles to magnetic nanoparticles and from magnetic nanoparticles to supported magnetic nanoparticles. We discussed various support materials and their synthesis methods, and applications, highlighting their unique features and advantages. Furthermore, we address the prospects in this rapidly advancing field, highlighting the potential for continued research and innovation to uncover new opportunities and tackle emerging societal needs.

1. Introduction

Magnetic nanoparticles (MNPs) are nanoscale particles (1 nm to 100 nm) made of magnetic materials that exhibit distinct magnetic behaviors compared to their bulk counterparts due to their small size and single-domain structure [1,2]. This includes superparamagnetic, where MNPs are magnetic only in the presence of an external field [3,4]. In contrast to ferromagnetism, where materials retain magnetization without an external field [5]. MNPs are broadly classified into ferromagnetic, superparamagnetic [6,7], and antiferromagnetic types, each with unique properties depending on size and structure [8].

Their quantum confinement and surface effects lead to unique behaviors such as enhanced magnetization [9], surface anisotropy [10], and altered exchange interactions [11]. These features make MNPs highly valuable in biomedical applications (*e.g.*, targeted drug delivery, MRI, hyperthermia) [12], data storage [13], and environmental remediation [14]. Their ease of manipulation *via* magnetic fields [15] and high surface reactivity opens up significant opportunities for innovation across diverse scientific and engineering domains [16,17]. Understanding these properties through the lens of nanomagnetism is crucial for further technological advancements [18].

Supported MNPs have gained popularity in many scientific and technical fields due to their numerous benefits over their free counterparts [19]. The enhanced stability offered by the support matrix, which is usually made up of substances *like* silica, polymers, or carbon-based substrates, is one of the main arguments for this change [20]. In applications where stability and dispersion are crucial, the support guarantees a more uniform distribution of nanoparticles and reduces agglomeration-related problems [21]. Furthermore, surface modification is made easier by switching to supported configurations, which enables customized functionalization of the MNPs [22].

This flexibility is essential for adjusting the nanocomposite's characteristics to match the unique demands of various applications [23]. In the field of biomedicine, the ability to combine supported MNPs with biocompatible supports allows for more precise targeted medication delivery and imaging applications. This demonstrates the adaptability of these particles [24]. Additionally, the use of supports enhances the magnetic properties of nanoparticles [25]. By preventing magnetic coupling and optimizing the spacing between nanoparticles, the support materials contribute to improved magnetic behavior [26]. The shift to supported MNPs also addresses practical considerations, such as ease of recovery and recyclability. Supported configurations, particularly those involving magnetic beads or recoverable supports, facilitate efficient separation processes through magnetic techniques [27]. This feature is advantageous in applications *like* environmental remediation, where the removal and reuse of the nanocomposite are essential for sustainable practices [28].

Supported magnetic nanoparticles (SMNPs) have emerged as a focal point of research in recent years, exciting scientists, and engineers alike due to their unique features and diverse uses [29]. The incorporation of MNPs onto various supports or substrates has evolved into a strategic technique for improving both their stability and functionality [30].

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This synergistic combination not only unleashes the full potential of MNPs but also broadens their application possibilities in a variety of disciplines [31]. One of the main reasons for using support materials is to reduce the proclivity of MNPs to aggregate [32]. The exploration of supported MNPs has unfolded as a dynamic chapter in the evolution of nanotechnology [34]. Magnetically supported nanoparticles provide some control over the magnetic characteristics of the composite system [33].

Emerging in the 1990s and gaining momentum into the early 2000s, this research area responded to the imperative of stabilizing and enhancing the functionality of MNPs [35]. Silica, revered for its stability and versatile surface properties, took center stage as a key support material, with researchers pioneering the synthesis of silica-coated magnetic nanoparticles [36]. This period marked a broader investigation into other support materials such as polymers, carbon-based substrates, and metal oxides, each offering unique attributes for specific applications [1]. The biomedical field witnessed a transformative impact as supported MNPs found applications in targeted drug delivery, magnetic resonance imaging (MRI), and hyperthermia therapy [37].

Among magnetocaloric materials, the nearly equiatomic iron-rhodium alloy is one of the most promising materials, as it exhibits the largest magnetocaloric effect in term of adiabatic temperature change [38]. Magnetic-supported nanoparticles show tremendous promise in the realm of medicine for targeted drug administration, hyperthermia therapy, and imaging modalities such as MRI [39]. In environmental science, the incorporation of magnetic nanoparticles onto support materials allows for the efficient remediation of contaminated water and soil, providing a long-term solution to pollution [40]. Concurrently, catalysis and environmental science benefited from the integration of these nanocomposites, showcasing their utility in diverse chemical reactions and pollution remediation [41]. The ability to modify support surfaces ushered in an era of tailored functionalization, enabling precise customization for various applications [42]. Recent developments continue to refine synthesis techniques, characterize supported systems, and explore novel applications, underscoring the ongoing significance of supported MNPs in shaping the landscape of advanced materials and their multidisciplinary impact [43].

This review offers a comprehensive overview of recent advancements in SMNPs, emphasizing their synthesis, structural advantages, and diverse applications. Unlike previous reviews, it highlights a comparative analysis of support materials and synthesis methods, offering insights into performance enhancement strategies. By bridging fundamental concepts with application-driven discussions, this work serves as a valuable resource for researchers aiming to design next-generation SMNPs for biomedical, environmental, and catalytic technologies.

2. Influence of supported materials on magnetic characteristics of nanoparticles

The SMNPs are hybrid materials in which magnetic nanoparticles are immobilized or embedded onto support matrices such as silica, polymers, carbon-based materials, or biopolymers [44]. These supports provide structural integrity and prevent the aggregation or oxidation of the nanoparticles. MNPs are inherently prone to agglomeration due to strong magnetic dipole–dipole interactions and high surface energies. This leads to a loss of surface area, reduced functionality, and instability in practical applications. Supporting them on stable materials not only disperses the particles uniformly but also enhances their mechanical, thermal, and chemical stability.

In addition to stabilization, the support material significantly influences the magnetic characteristics of the nanoparticles—such as coercivity, saturation magnetization, and anisotropy—by altering interparticle spacing, surface interactions, and domain structures. Understanding these effects is essential for tailoring SMNPs for specific applications, which is discussed in detail in the following subsections.

The following are some key aspects to consider in the influence of support materials on the magnetic characteristics of specific nanoparticles:

2.1 Magnetic interactions

Support materials can interact differently with magnetic nanoparticles (MNPs), affecting their magnetic behavior. For instance, materials with high electrical conductivity or specific crystal structures may enhance or modify the magnetic moment of MNPs through exchange interactions or magnetic coupling.

2.2 Size and shape control

Support materials often influence the size, shape, and crystallinity of MNPs during synthesis. These factors are critical as they dictate the magnetic domain structure and coercivity of the nanoparticles, which are essential for applications *like* magnetic storage media or magnetic hyperthermia in biomedicine.

2.3 Surface functionalization

Support materials provide a stable platform for surface functionalization of MNPs. Functional groups attached to the support can alter the surface chemistry of MNPs, affecting their magnetic properties such as colloidal stability, magnetic relaxation times, and interactions with biological environments in biomedical applications [29].

2.4 Magnetic anisotropy

The arrangement of MNPs on a support material can induce magnetic anisotropy, influencing the directionality of magnetic moments within the nanoparticles. This is crucial for applications requiring controlled magnetic alignment, such as in magnetic sensors or magneto-optical devices. Additionally, supported MNPs often exhibit altered blocking temperatures (T_B) and coercivity, depending on particle size, shape, and the nature of the support. These magnetic parameters are critical in determining the superparamagnetic behavior of MNPs, which is essential for biomedical applications such as MRI contrast agents and magnetic hyperthermia. For example, a higher T_B can improve thermal stability in hyperthermia, while low coercivity is preferred in MRI to avoid remanence.

2.5 Stability and durability

The choice of support material impacts the overall stability and durability of MNPs under different environmental conditions. For example, inert or chemically robust supports can prevent oxidation or degradation of MNPs, maintaining their magnetic properties over extended periods.

2.6 Enhanced properties

Certain support materials can enhance specific magnetic properties of MNPs. For instance, carbon-based supports *like* graphene or carbon nanotubes can improve electron transfer processes, enhancing the efficiency of MNPs in catalytic applications involving magnetic nanocomposites [45].

In conclusion, understanding how support materials influence the magnetic characteristics of nanoparticles involves a multifaceted analysis of their structural, chemical, and physical interactions. Tailoring support materials to optimize desired magnetic properties is essential for advancing applications ranging from biomedical diagnostics and therapy to environmental remediation and information storage technologies. Continued research in this area holds promise for developing next-generation magnetic nanomaterials with enhanced performance and versatility [46].

3. Magnetic nanoparticles and support materials

Various support materials play a major role in stabilizing and improving the properties of magnetic nanoparticles, facilitating their diverse applications in fields ranging from biomedicine to environmental remediation [47]. Silica, with its high surface area and stability, offers excellent support for MNPs, ensuring their dispersion and preventing aggregation [48]. Alumina, known for its robustness and chemical inertness, provides a durable platform for MNPs, enhancing their mechanical strength and resistance to harsh conditions. Cellulose, a renewable and biocompatible material, serves as an environmentally friendly support for MNPs, enabling applications in biomedical and environmental fields. Charcoal, with its porous structure and adsorption capabilities, offers an effective support matrix for MNPs, facilitating their use in purification and filtration processes. Each support material brings unique advantages to MNPs, contributing to their versatility and efficacy in various applications. Various MNPs and support materials are shown in Figure 1.

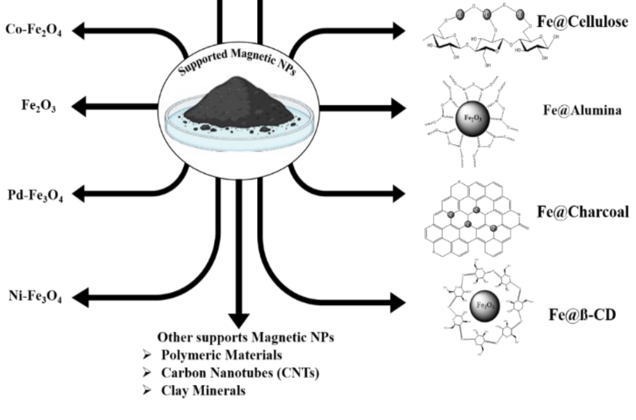


Figure 1. Magnetic nanoparticles and various support materials.

In the realm of MNPs, understanding their quantitative magnetic characteristics is paramount. These properties dictate their behavior in various applications, ranging from targeted drug delivery to MRI. As we explore different classes of supported MNPs, we delve into their magnetic responses, coercivity, saturation magnetization, and hysteresis behavior. By quantifying these features, researchers can tailor MNPs for specific functions, optimizing their performance in diverse contexts [49].

Each support material provides unique advantages and influences the magnetic properties of the nanoparticles, making them suitable for specific applications. Silica and alumina support offer high stability and low aggregation, making them ideal for biomedical and catalytic applications. Cellulose supports provide biocompatibility and biodegradability, which are beneficial for drug delivery and environmental applications. Charcoal supports offer high adsorption capacity, useful in water treatment, while polymeric materials provide flexibility and enhanced mechanical properties for drug delivery and sensor applications.

3.1 Silica-supported magnetic nanoparticles

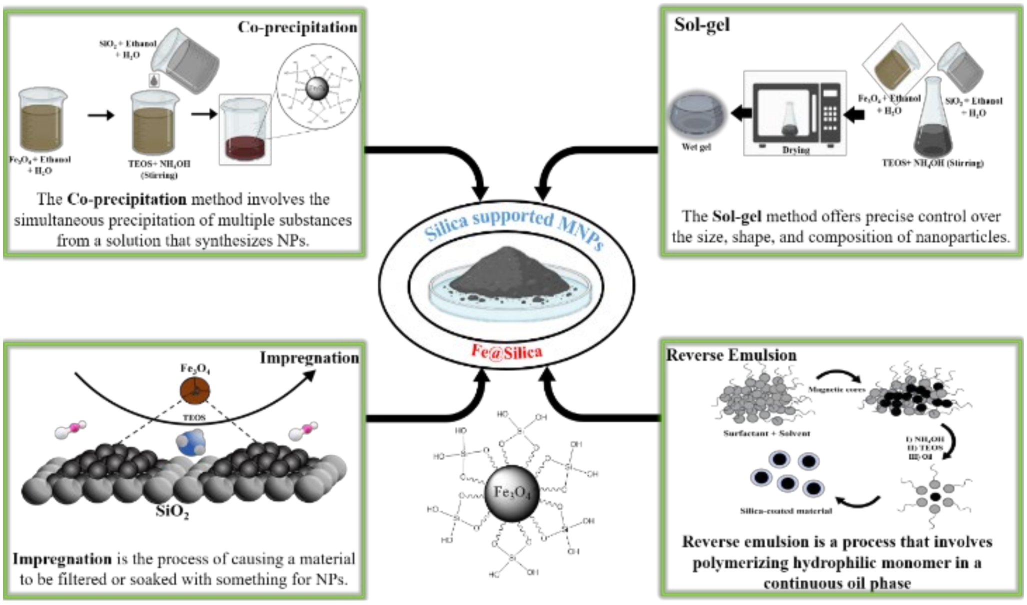
Silica, as a support material for MNPs, has emerged as a keystone in the realm of nanotechnology, contributing significantly to the evolution of advanced materials [50]. Silica coating for MNPs has become a promising and important approach in the development of MNPs for both fundamental study and technological research [51]. Silica-coated MNPs form due to the interactions such as surface adsorption, covalent bonding, or electrostatic forces between silica and the magnetic core. These interactions enhance the performance of the modified silica in various applications. The history of silica's utilization as a support material gained momentum with its notable presence in early investigations in the 1990s and has since become a primary focus of research [52]. Its surface, easily modifiable for tailored functionalization, has allowed researchers to fine-tune the properties of the resulting nanocomposites. Synthetic methods of silica-supported MNPs are shown in Figure 2.

3.1.1 Synthesis of silica-supported magnetic nanoparticle

Coprecipitation method for synthesizing silica supported magnetic nanoparticles

The coprecipitation method is a widely employed technique for synthesizing silica-supported MNPs due to its simplicity and effectiveness. S. Wang *et al.* presented a coprecipitation method for synthesizing silica-coated Fe_3O_4 nanoparticles (NPs). Notably, the synthesized Fe_3O_4 NPs exhibited excellent magnetic properties, with high saturation magnetization ($M_s = 93$ emu·g^{-1}) and low coercivity ($H_c = 110$ Oe) [53].

D. V. Quy *et al.* group produced magnetic Fe_3O_4 NPs *via* coprecipitation and subsequently coated them with silica. The magnetic core of these Fe_3O_4/SiO_2 nanoparticles measured 10 nm to 15 nm, whereas the silica shell had a thickness of 2 nm to 5 nm. A VSM verified the Fe_3O_4/SiO_2 particle's superparamagnetic property, indicating a magnetization of 42.5 emu·g^{-1} [54]. Aygar *et al.* group created cobalt ferrite ($CoFe_2O_4$) NPs with a surface-modified nickel nitriloacetic acid (Ni-NTA) affinity group and used them to separate proteins tagged



The **Co-precipitation** method involves the simultaneous precipitation of multiple substances from a solution that synthesizes NPs.

The **Sol-gel** method offers precise control over the size, shape, and composition of nanoparticles.

Impregnation is the process of causing a material to be filtered or soaked with something for NPs.

Reverse emulsion is a process that involves polymerizing hydrophilic monomer in a continuous oil phase

Figure 2. Strategies to synthesize silica-supported magnetic nanoparticles.

with histidine from intricate matrices by employing the imidazole side chains of histidine molecules. Firstly, the controlled coprecipitation approach was used to create $CoFe_2O_4$ NPs with a limited dimension distribution in an aqueous solution. Sodium chloride and oleic acid were employed as dispersants to produce tiny $CoFe_2O_4$ agglomerates. After coating the $CoFe_2O_4$ particles with SiO_2, amine (NH_2) groups were added to their surface (forming SiO_2-$CoFe_2O_4$) to provide additional functional groups to the silica shell. $CoFe_2O_4$ NPs exhibited cubic morphology, homogeneous size distribution, and a pure phase structure. The optical band gap was tuned from 1.147 eV to 0.92 eV. Saturation magnetization increased from 53.91 emu·g^{-1} to 84.01 emu·g^{-1} after annealing at 700°C. Coercivity enhanced from 1137 Oe to 2109 Oe at room temperature, which is the highest reported value for $CoFe_2O_4$ NPs synthesized *via* thermal decomposition [55].

These variations in saturation magnetization values highlight the importance of considering both the structural design and measurement parameters. It is noteworthy that such values are often influenced by the normalization basis, whether calculated per unit mass of the magnetic core or the entire core–shell composite. Furthermore, differences in shell thickness also play a significant role, as thicker non-magnetic shells reduce the effective magnetization per gram of material. These factors complicate direct comparisons across different systems and must be carefully accounted for when evaluating magnetic performance.

Mahmed *et al.* group synthesized iron oxide NPs, or magnetite, utilizing solely iron(II) ions (Fe^{2+}) as a precursor in an ambient environment. By utilizing two synthesis methods, the room temperature reverse coprecipitation approach was employed. The Stöber silica (SiO_2) layer was applied right away to the freshly produced iron oxide, creating the core-shell structure [56].

Sol-gel method for synthesizing silica-supported magnetic nanoparticles

The sol-gel process includes converting a solution (sol) into a gel, and then into a solid substance. The sol-gel method is a useful approach for synthesizing silica-supported MNPs, providing precise control over the size, structure, and surface characteristics of the particles [57]. Iron(III)chloride was used as the starting material for the reduction-precipitation process to create magnetite nanoparticles. Na_2SO_3 then partially reduced the iron to iron(II) salts, which were then alkalized with ammonia. When using the sol-gel technique, the particles were covered with aqueous solutions of ammonia or HCl to facilitate base- or acid-catalyzed hydrolysis, respectively. Ranjbakhsh *et al.* group produced Fe_3O_4 NPs coated with silica by the sol-gel method of tetraethyl orthosilicate (TEOS) hydrolysis. These nanoparticles exhibit a high saturation magnetization of approximately 93 emu·g^{-1} at room temperature [58].

Deng's group investigated the production of SiO_2 coated magnetite particles using a sol-gel technique. The results show that several reaction parameters play important roles in the formation of silica-coated magnetite particles and the superparamagnetic semicharacteristics of the resulting silica-coated MNPs. These parameters include the type of alcohol, the volume ratio of alcohol to water, the amount of catalyst, and the amount of precursor. The synthesized Fe_3O_4@ SiO_2 NPs exhibit excellent magnetic properties, including a high saturation magnetization (Ms) of approximately 20.83 emu·g^{-1} [59].

Changzi Jin's group prepared Using a sol-gel method and pseudomorphic transformation, a hierarchically organized silica shell that covers iron oxide MNPs in a core-shell nanocomposite [60].

Reverse emulsion method for synthesizing silica-supported magnetic nanoparticles

The reverse emulsion method is a versatile approach for synthesizing silica-supported MNPs, offering precise control over particle size and morphology. This process creates a water-in-oil emulsion, with the water phase containing the silica precursor, a surfactant or emulsifying agent (cetyltrimethylammonium bromide, CTAB), and an acid or base catalyst [61]. Zhang's group investigated the use of XRD, TEM, and a superconducting quantum interference device (SQUID) in the modified reverse microemulsion process for the systematic synthesis of silica-coated MNPs. The findings indicate that the concentration of the reaction agents could regulate the silica shell's thickness and that the surfactant Igepal CO-520 was a significant component of the reaction system. With a thin silica shell of around 2 nm, the produced ultra-thin silica-coated MNPs have a high saturation magnetization of approximately 15 emu·g^{-1} [62]. Tanveer Ahmad and Ilsu Rhee produced biocompatible silica to coat the iron-oxide (Fe_3O_4) nanoparticles, which were made utilising the reverse micelle technique. The TEM pictures of the coated nanoparticles revealed a consistent size distribution and spherical shape with an average diameter of 10 nm. Using a magnetic resonance (MR) scanner, the T1 and T2 relaxation durations of hydrogen protons in aqueous solutions with different concentrations of silica-coated nanoparticles were found [63].

Impregnation method for synthesizing silica-supported magnetic nanoparticles

The impregnation method is a versatile approach for synthesizing silica-supported MNPs, providing control over the dispersion of active species on the silica support [64]. Mevellec's group prepared Rhodium nanoparticles as colloidal suspensions in aqueous solution by chemically reducing the precursor $RhCl_3.3H_2O$ in the presence of the surfactant *N*,*N*-dimethyl-*N*-cetyl-*N*-(2-hydroxyethyl) ammonium chloride ($HEA1_6Cl$). The rhodium nanoparticles were then immobilized on silica by straightforward impregnation. After the surfactant is eliminated and the silica is immobilized, an increase in particle size of 2.4 nm to 5 nm has been observed [65].

3.2 Alumina as a support material for magnetic supported nanoparticles

Alumina, or aluminum oxide (Al_2O_3), is a versatile and widely employed support material due to its exceptional thermal stability, high surface area, and chemical inertness [66]. Researchers started looking into the use of different support materials to attach and stabilize magnetic species in the middle of the 20th century, which is when alumina first appeared on the scene as MNPs support material [34]. In the context of supported MNPs, alumina gained prominence as an effective support matrix that enhances the dispersibility and stability of MNPs [67]. The first notable applications emerged in the field of heterogeneous catalysis, where MNPs supported on alumina surfaces exhibited enhanced catalytic activity and recyclability [68]. The synthetic method of alumina-supported MNPs is shown in Figure 3.

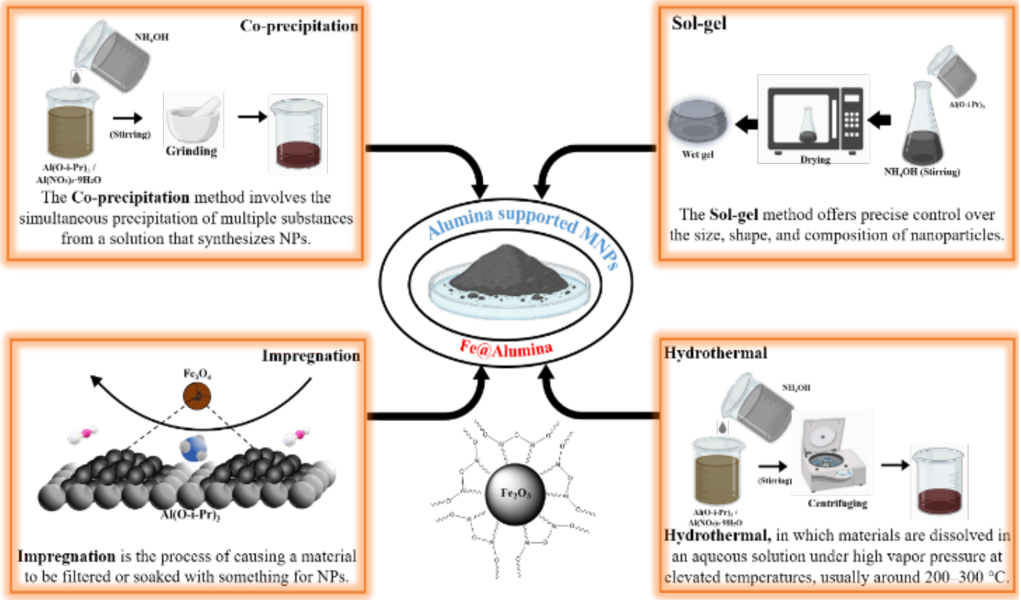
Concluding remarks

Sol-gel method is best for synthesizing silica-supported MNPs. The sol-gel method offers precise control over the size, shape, and composition of NPs. By adjusting parameters such as precursor concentration, temperature, and pH, you can adjust the nanoparticle's size and magnetic characteristics to fit your needs [69].

One of the key advantages of the sol-gel method lies in its ability to produce MNPs with uniform size distributions and well-defined shapes, critical for applications in magnetic data storage, biomedical diagnostics, and environmental remediation. This level of control ensures consistency in magnetic properties, enhancing performance reliability across various technological domains [70].

Compared to alternative synthesis approaches *like* coprecipitation or thermal decomposition, the sol-gel method excels in providing a stable and homogeneous silica matrix that supports MNPs without compromising their magnetic functionalities. This stability is crucial for applications requiring robust materials capable of withstanding harsh environmental conditions or demanding performance criteria [56].

Furthermore, silica's intrinsic properties as a support material contribute significantly to the effectiveness of MNPs synthesized *via* the sol-gel method. Silica offers excellent chemical and thermal stability, high surface area, and tunable surface chemistry, facilitating enhanced dispersibility and compatibility with biological systems. These attributes make silica-supported MNPs well-suited for biomedical applications such as targeted drug delivery, MRI contrast agents, and biosensors [29].



The **Co-precipitation** method involves the simultaneous precipitation of multiple substances from a solution that synthesizes NPs.

The **Sol-gel** method offers precise control over the size, shape, and composition of nanoparticles.

Impregnation is the process of causing a material to be filtered or soaked with something for NPs.

Hydrothermal, in which materials are dissolved in an aqueous solution under high vapor pressure at elevated temperatures, usually around 200–300 °C.

Figure 3. Strategies for synthesizing alumina-supported magnetic nanoparticles.

In summary, the sol-gel method represents a superior approach for synthesizing silica-supported MNPs, combining meticulous control over nanoparticle properties with the inherent advantages of silica as a support material. Leveraging this method's precision and versatility enables researchers to innovate across a broad spectrum of applications, from advanced materials in electronics to biomedical devices, promising advancements in magnetic nanotechnology and interdisciplinary research [19].

3.2.1 Synthesis of alumina-supported magnetic nanoparticles

Coprecipitation method for synthesizing alumina-supported magnetic nanoparticles

The coprecipitation method is a widely employed technique for the synthesis of alumina-supported magnetic nanoparticles. In this process, metal precursors, typically metal salts, are simultaneously precipitated with a base in the presence of alumina particles. Lei Sun's group studied a novel kind of sodium dodecyl sulfate (SDS)-modified alumina-coated MNPs (Fe_3O_4/Al_2O_3) that are employed in mixed hemimicelles solid-phase extraction (MHSPE) to extract trimethoprim (TMP) from ambient water samples. Fe_3O_4 NPs coated with alumina not only keep Fe_3O_4 NPs from dissolving in an acidic solution, but their application is also increased without sacrificing their unique magnetic characteristics. The coercivity of hemimicelles solid-*like* Fe_3O_4 NPs increased to a maximum of 190 Oe at a critical size of approximately 76 nm. This suggests strong exchange interactions during spin alignment [70].

D. Karabelli's group used a composite sorbent (Al-nZVI) used to extract Cu^{2+} ions from aqueous solutions, consisting of iron nanoparticles and alumina. Fe^{2+} ions were converted to metallic iron nanoparticles by adding alumina to the solution and employing borohydride ions as a catalyst. The characterization results demonstrated that the iron nanoparticles, which had sizes ranging from 10 nm to 80 nm, were partially dispersed on the alumina surface. The composite sorbent demonstrated fast uptake, with a fixation capacity of $1.50\ mmol{\cdot}g^{-1}$ ($95.3\ mg{\cdot}g^{-1}$). This capacity is significantly higher than that of pure alumina ($0.32\ mmol{\cdot}g^{-1}$; $20.3\ mg{\cdot}g^{-1}$) [71].

Sol-gel method for synthesizing alumina-supported magnetic nanoparticles

The sol-gel method is a flexible and popular approach for synthesizing alumina-supported nanoparticles with precise command over surface characteristics, composition, and structure [1]. Zhixin Yao's group studied, FeNiMo@Al_2O_3 Powders covered with sol-gel and burned at 900°C to 1300°C were made and pressed into SMCs. The results showed that the powder's surface was uniformly coated in Al_2O_3 [72].

Hydrothermal method for synthesizing alumina-supported magnetic nanoparticles

The hydrothermal method is a widely used technique for synthesizing alumina-supported MNPs, providing a controlled and efficient process for nanoparticle formation. In this method, metal precursors are typically mixed with an alumina precursor in an aqueous solution [73]. The mixture is then sealed in a high-pressure reactor and subjected to elevated temperatures and pressures for a specific duration. During the hydrothermal treatment, the metal precursors undergo nucleation and subsequent growth, resulting in the formation of magnetic NPs on the surface of the alumina support [74].

Impregnation method for synthesizing alumina-supported magnetic nanoparticles

To synthesize alumina-supported MNPs using the impregnation method, the process typically involves several steps. First, the alumina support material, often in the form of nanoparticles or a porous structure, is prepared [75]. This can involve methods such as sol-gel synthesis or precipitation. Jo-yong Park's group investigated a fixed-bed reactor to explore Iron oxide at the nanoscale supported by δ-Al_2O_3. The catalysts made from pre-synthesized iron oxide with varied particle sizes (2 nm to 12 nm) demonstrated much greater catalytic activity than those made using the standard impregnation method [76].

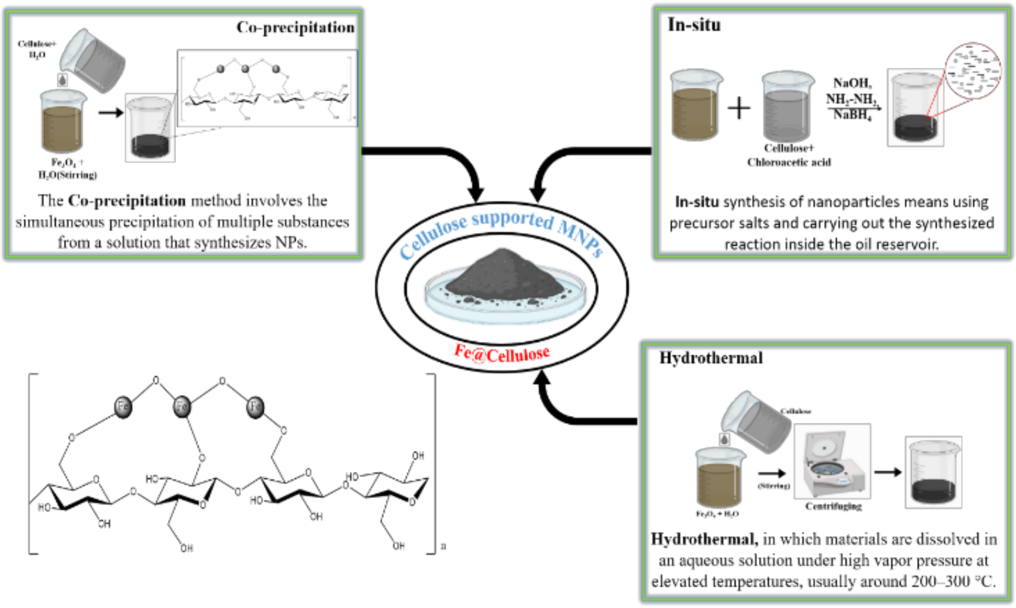
Concluding remarks

In comparison to alternative synthesis techniques *like* hydrothermal synthesis or sol-gel methods, coprecipitation excels in efficiency and cost-effectiveness. It operates under mild conditions and typically yields homogeneous dispersions of MNPs on alumina supports, minimizing the need for complex post-synthesis treatments. These attributes streamline production processes and reduce overall manufacturing costs, making coprecipitation particularly attractive for industrial applications demanding high throughput and consistency [24].

3.3 Cellulose as support material for magnetic nanoparticles

Cellulose-supported MNPs have emerged as versatile materials with promising applications in various fields, owing to their exclusive combination of properties [77]. The integration of cellulose, a biocompatible and renewable polymer, with MNPs has garnered considerable interest due to its potential in biomedical, environmental, and industrial applications [78]. The concept of combining cellulose with MNPs traces back to the early 2000s when researchers began exploring methods to immobilize MNPs onto cellulose matrices [79]. Initial efforts focused on synthesizing MNPs with functional groups capable of interacting with cellulose surfaces, enabling their attachment *via* chemical or physical means [80].

Various techniques, including coprecipitation, sol-gel, hydrothermal synthesis, and surface modification, have been developed to tailor the size, morphology, and magnetic properties of the nanoparticles while ensuring their effective integration with cellulose matrices [81]. Synthetic methods of cellulose-supported MNPs are shown in Figure 4. In biomedicine, these hybrid materials have shown promise in targeted medication delivery, MRI, hyperthermia therapy, and bioseparation processes [82]. Moreover, ongoing research efforts focus on exploring novel applications and improving the performance of these materials through advances in synthesis techniques, surface functionalization, and understanding their fundamental properties [83].



The **Co-precipitation** method involves the simultaneous precipitation of multiple substances from a solution that synthesizes NPs.

In-situ synthesis of nanoparticles means using precursor salts and carrying out the synthesized reaction inside the oil reservoir.

Hydrothermal, in which materials are dissolved in an aqueous solution under high vapor pressure at elevated temperatures, usually around 200–300 °C.

Figure 4. Strategies to synthesize cellulose-supported magnetic nanoparticles.

3.3.1 Synthesis of cellulose-supported magnetic nanoparticles

Coprecipitation method for synthesizing cellulose-supported magnetic nanoparticles

In this method, iron salts such as $FeCl_2$ and $FeCl_3$ are typically dissolved in an alkaline solution under inert gas conditions, followed by the addition of cellulose. This results in the precipitation of iron oxide NPs on the cellulose surface. The process is often carried out under controlled conditions to regulate the size, morphology, and magnetic properties of the NPs [84]. Jiaying Zhang's group described a new core-shell structured nanomaterial made of Fe_3O_4 NPs with 2,3-dialdehyde nanocrystalline cellulose (DAC) covering, as well as its remarkable efficiency in glycoprotein preconcentration. After the production of aldehyde groups by periodate oxidation of nanocrystalline cellulose, Fe_3O_4 NPs were coated with DAC, which were subsequently connected to 4-aminophenylboronic acid (PBA) to form PBA-functionalized magnetic core-shell structured materials (Fe_3O_4@DAC). The Fe_3O_4 NPs coated with DAC (Fe_3O_4@DAC) exhibit a saturation magnetization of approximately 69.50 emu·g^{-1} [85]. C. Wan and Jian Li conducted a simple oxidative coprecipitation procedure to distribute $CoFe_2O_4$ nanoparticles throughout the matrixes of the cellulose aerogel, and a green NaOH/polyethylene glycol solution was used to prepare the native wheat straw for the cellulose aerogels [86].

In- situ method for synthesizing cellulose-supported magnetic nanoparticles

This approach involves the synthesis of magnetic nanoparticles directly within a cellulose matrix. Iron precursors are introduced into a cellulose solution, followed by the addition of reducing agents and stabilizers. The reduction of iron ions and subsequent nucleation and growth of nanoparticles occur within the cellulose matrix, leading to the formation of cellulose-supported MNPs [87]. S. Keshipour's group placed Fe_3O_4 and Palladium nanoparticles on cellulose functionalized with N-(2-aminoethyl) acetamide in preparation for a catalytic reaction. The catalyst was employed in the H_2O_2-catalyzed oxidation process of ethylbenzene at 100°C [88].

Hydrothermal synthesis method for synthesizing cellulose-supported magnetic nanoparticles

Hydrothermal or solvothermal methods involve the synthesis of MNPs within a cellulose hydrogel under high-pressure and high-temperature conditions. Cellulose acts as both a template and a stabilizing agent during the formation of MNPs, leading to the encapsulation or immobilization of nanoparticles within the cellulose network [89].

Concluding remarks

The coprecipitation method emerges as a robust choice for synthesizing cellulose-supported magnetic nanoparticles (MNPs), offering distinct advantages in both synthesis efficiency and nanoparticle characteristics. Its straightforward implementation makes it accessible to researchers across different disciplines, reducing the technical barriers associated with nanoparticle synthesis on cellulose substrates.

Compared to alternative techniques *like* sol-gel or microwave-assisted methods, coprecipitation stands out for its simplicity and scalability. The method allows for precise control over nanoparticle size, morphology, and surface chemistry by adjusting reaction parameters such as temperature, pH, and precursor concentrations. This control is essential for tailoring the properties of cellulose-supported MNPs to meet specific application requirements, including improved magnetic responsiveness, enhanced stability in biological environments, and efficient pollutant adsorption.

Furthermore, the choice of cellulose as a support material offers additional benefits. Cellulose is biocompatible, abundant, and renewable, making it an environmentally friendly substrate for MNPs. The cellulose matrix provides a stable and biocompatible environment for nanoparticles, facilitating their integration into various biomedical and environmental applications [90].

In conclusion, the coprecipitation method represents a versatile and effective approach for synthesizing cellulose-supported MNPs, combining ease of implementation with precise control over nanoparticle properties. Leveraging the unique advantages of cellulose as a support material, coprecipitation opens doors to innovative solutions in fields ranging from biomedicine to environmental remediation, promising advancements in sustainable nanotechnology and practical applications.

3.4 Charcoal as support material for magnetic nanoparticles

The development of charcoal-supported MNPs represents a convergence of advancements in nanotechnology, materials science, and environmental remediation. The history of this innovative approach can be traced back to the early 21st century when investigators began discovering the synthesis and applications of MNPs [91]. Initially, MNPs were predominantly used in biomedical applications such as drug delivery and imaging. However, their unique properties, including high surface area and magnetic responsiveness, soon attracted attention for environmental remediation purposes [92]. Concurrently, the use of charcoal, known for its porous structure and adsorption capabilities, gained traction in various fields, particularly in water and air purification. The combination of charcoal and MNPs emerged as a synergistic solution to address environmental challenges more effectively [93]. Over time, researchers refined synthesis techniques to immobilize MNPs onto charcoal substrates, enhancing their stability, dispersibility, and adsorption capacity. Synthetic methods of charcoal-supported MNPs are shown in Figure 5.

3.4.1 Synthesis of charcoal or carbon-based material supported magnetic nanoparticles

Coprecipitation method for synthesizing charcoal supported nanoparticles

Charcoal is a carbon-rich material primarily derived from organic sources through pyrolysis or destructive distillation processes. It typically retains some of the original cellular structure of the source material, resulting in a porous, heterogeneous material. Charcoal is known for its high surface area and adsorption capabilities, making it suitable for various applications such as filtration, adsorption of contaminants, and as a support material for nanoparticles [94].

On the other hand, carbon-based materials encompass a broader category that includes charcoal but extends to materials *like* activated carbon, graphene, carbon nanotubes, and carbon black. These materials vary widely in structure, surface area, and properties depending on their synthesis methods and processing conditions. For instance, activated carbon is a highly porous form of carbon with an extensive internal surface area, ideal for adsorption applications [95].

When discussing the use of charcoal as a support material for magnetic nanoparticles, it is crucial to recognize these distinctions. While the literature on carbon-based materials often encompasses studies on activated carbon, graphene, and other forms of carbon, specific investigations into charcoal's interactions with magnetic nanoparticles highlight its unique properties and potential applications [96]. Therefore, while charcoal shares similarities with other carbon-based materials, its distinct characteristics, such as its origin, structure, and surface chemistry, warrant specific attention in studies focusing on its role as a support matrix for magnetic nanoparticles [97].

In this method, iron salts (such as $FeCl_2$ and $FeCl_3$) are dissolved in an aqueous solution and then precipitated by adding a base (such as NaOH or NH_4OH) under inert gas or vacuum conditions [98]. Simultaneously, charcoal nanoparticles are dispersed in the solution. The resulting mixture undergoes vigorous stirring and heating, leading to the formation of MNPs coated or anchored onto the surface of charcoal [99]. This method offers simplicity and scalability but may require additional steps for surface modification and stabilization. L.M.M Prieto *et al.* presented encapsulated magnetic FeCo and CoNPs in carbon (Co@C and FeCo@C) as an ultra-stable heating material suitable for high-temperature magnetic catalysis. Indeed, FeCo@Co a mixture of FeCo@C:Co@C (2:1) decoratedwith Ni or Pt−Sn showed good stability in terms of temperature and catalytic performances [100]. Junli Wan's group examined the effectiveness of magnetic manganese ferrite NPs produced on powdered activated

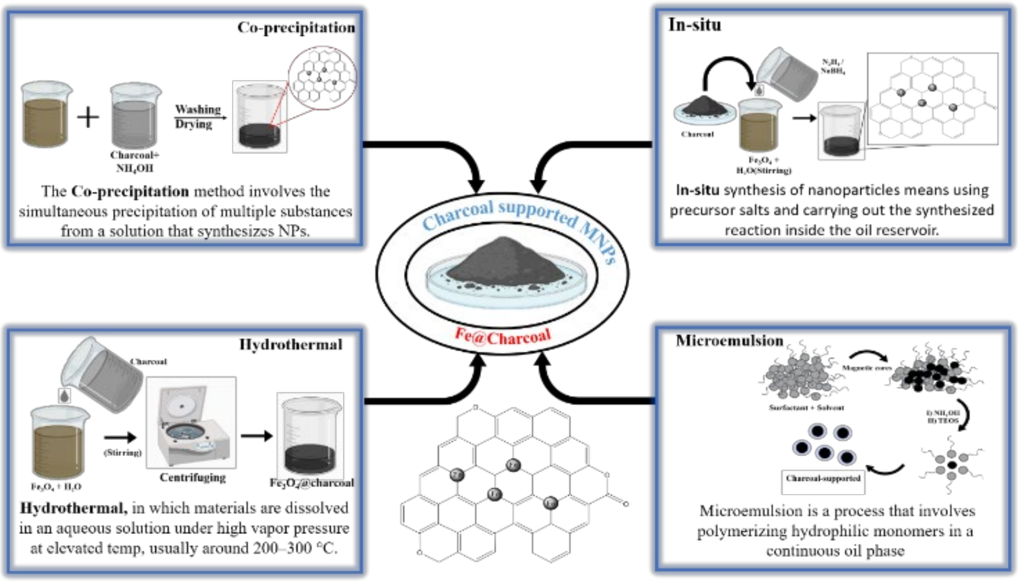


Figure 5. Strategies to synthesize charcoal supported magnetic nanoparticles.

carbon (PAC) for the elimination of sulfamethoxazole (SMX) from aqueous solution. Utilizing chemical coprecipitation at various temperature ranges between 298 K and 423 K, magnetic activated carbon composites (MACC) were created [101].

Hydrothermal or solvothermal method for synthesizing charcoal supported magnetic nanoparticles

In hydrothermal or solvothermal synthesis, iron precursors and carbon sources (such as glucose or sucrose) are mixed in a suitable solvent and sealed in a high-pressure reactor [102]. The reaction mixture is heated at elevated temperatures (typically above 100°C) for a certain duration, allowing for the nucleation and growth of MNPs on the surface of charcoal [103]. This method offers tunability of particle size, morphology, and crystallinity and can be performed in aqueous or organic solvents. Nianwu Lu's group created magnetic $CoFe_2O_4$-functionalized graphene sheets ($CoFe_2O_4$–FGS) nanocomposites by hydrothermally treating inorganic salts and thermally sandblasted graphene sheets. Cobalt ferrite nanoparticles with diameters ranging from 10 nm to 40 nm are evenly distributed over graphene sheets. The $CoFe_2O_4$-functionalized graphene sheets ($CoFe_2O_4$-FGS) nanocomposites exhibit a saturation magnetization of approximately 69.50 $emu\cdot g^{-1}$ [104]. Mohan's group prepared magnetite (Fe_3O_4) nanoparticles supported on graphene, charcoal, or SBA-15 using a straightforward solid-state grinding method followed by a heat treatment. The Fe_3O_4 NPs supported on activated charcoal demonstrated high catalytic activity and provided good yields of the alkynyl selenide product in the cross-coupling reaction of diphenyl diselenide and alkynes through activation of C–H and Se–Se bonds under environmentally friendly conditions, outperforming conventional copper-based catalysts to effect the same organic transformation [91,105].

Microemulsion method for synthesizing charcoal supported magnetic nanoparticles

In this method, a microemulsion system consisting of water, oil, surfactant, and co-surfactant is prepared. Iron precursors are dissolved in the aqueous phase, while charcoal nanoparticles are dispersed in the oil phase. Under controlled conditions, the two phases are mixed, leading to the formation of magnetic nanoparticles within the microemulsion droplets [106]. Upon heating or chemical treatment, the MNPs coated with surfactant molecules are deposited onto the surface of charcoal nanoparticles. This method offers excellent control over particle size and mono dispersity and can be scaled up for industrial production [107].

In-situ reduction method for synthesizing charcoal supported magnetic nanoparticles

In this approach, iron(II) or iron(III) chloride precursors are directly reduced in the presence of charcoal NPs to form MNPs on the surface of charcoal. This can be achieved through various reducing agents, such as sodium borohydride or hydrazine, under mild reaction conditions [108]. The in-situ reduction method offers simplicity and control over nanoparticle size and distribution and can be performed in aqueous or non-aqueous solvents [109]. Yi Zhang's group prepared magnetic bio-nanoparticles to measure hydroquinone and adhered to the carbon paste electrode surface using a permanent magnet. The immobilization matrix offered a favourable milieu for laccase to maintain its bioactivity [110].

Concluding remarks

The coprecipitation method emerges as the optimal choice for synthesizing charcoal supported magnetic nanoparticles (MNPs). This versatile method involves the simultaneous precipitation of nanoparticles onto charcoal substrates in a single step, making it highly cost-effective and suitable for scalable production. By adjusting critical parameters such as temperature, pH, and precursor concentrations, the coprecipitation method enables precise control over the size, morphology, and composition of the synthesized nanoparticles. Such control is crucial for tailoring the properties of charcoal-supported MNPs to meet specific application requirements, spanning from environmental remediation to catalysis and biomedical applications [111].

In comparison to alternative synthesis approaches, the coprecipitation method offers distinct advantages. Its simplicity and efficiency facilitate economical production without the need for complex post-treatment steps. This method's ability to accommodate a wide range of nanoparticle precursors (*e.g.*, metal, metal oxide, carbon-based) and charcoal substrates (*e.g.*, activated carbon, biochar) underscores its versatility in producing diverse types of MNPs with tailored functionalities. This versatility is particularly advantageous in applications where the choice of nanoparticle material and support substrate significantly impacts performance and stability.

The selection of charcoal as a support material further enhances the properties of MNPs synthesized *via* coprecipitation. Charcoal's high surface area and porous structure provide ample sites for nanoparticle anchoring and subsequent functionalization. This characteristic makes charcoal-supported MNPs highly effective in applications such as water purification, gas adsorption, and sensing technologies, where surface area and reactivity are critical.

In summary, the coprecipitation method stands out for its versatility, cost-effectiveness, and ability to tailor nanoparticle characteristics through straightforward parameter adjustments. Coupled with charcoal as a support substrate, this method offers a promising pathway for developing advanced magnetic nanomaterials with enhanced functionalities, poised to address a wide range of environmental, industrial, and biomedical challenges.

3.5 β-Cyclodextrin as support material for magnetic nanoparticles

β-cyclodextrin (β-CD) serves as an excellent support material for MNPs in various applications due to its unique structure and properties. By functionalizing β-CD and anchoring it onto the surface of MNPs, a stable and versatile platform is created. Additionally, the nanoparticle's magnetic characteristics make it simple to separate and recover using an external magnetic field, improving productivity and recyclability. Thus, the combination of β-CD and MNPs holds significant promise for applications such as drug delivery, environmental remediation, and catalysis [112]. Synthetic methods of β-CD supported MNPs are shown in Figure 6.

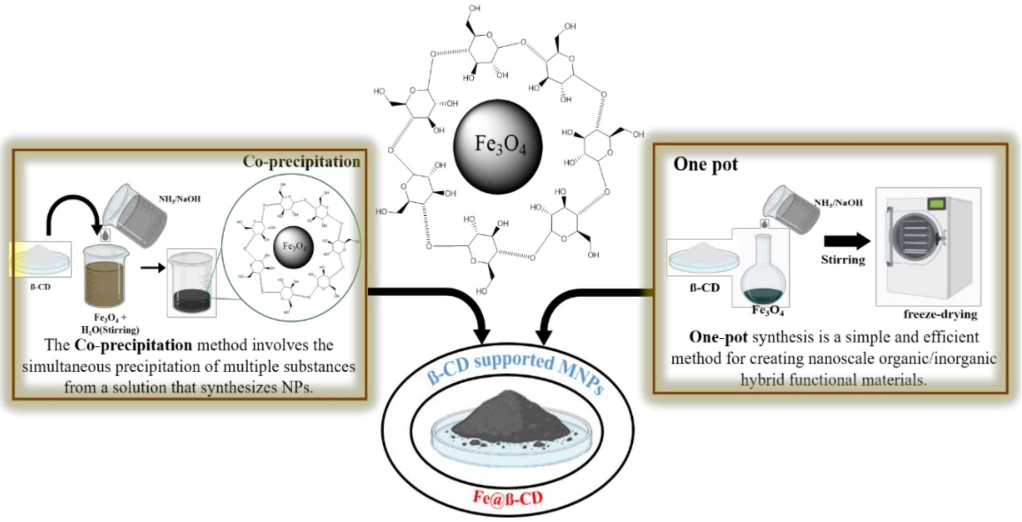


Figure 6. Strategies to synthesize β-cyclodextrin supported magnetic nanoparticles.

3.5.1 Synthesis of β-cyclodextrin-supported magnetic nanoparticles

One-pot synthesis

A one-pot synthesis involving β-CD and magnetic nanoparticles offers a streamlined approach to the fabrication of functional materials with diverse applications [113]. In this synthesis strategy, all reaction steps occur within a single reaction vessel, simplifying the process and reducing the need for intermediate purification steps [114]. Kaboudin's group described the synthesis of symmetrical biaryls and 1,2,3-triazoles from arylboronic acids using an effective, readily recoverable, and reusable Fe_3O_4 MNPs-supported Cu(II)-β-CD complex catalyst. The Cu(II)-β-CD complex catalyst supported by Fe_3O_4 magnetic nanoparticles was reported, which exhibits a saturation magnetization of approximately 54.6 emu·g^{-1} [115].

Coprecipitation synthesis

Coprecipitation synthesis is a common method for the synthesis of MNPs, including those supported by β-CD. In this method, salts of the desired metals, typically iron, nickel, or cobalt, are dissolved in a suitable solvent, often water. Then, a precipitating agent, such as a base (*e.g.*, sodium hydroxide or ammonia), is added to the solution under controlled conditions, leading to the formation of metal hydroxide precipitates. X. Huang's group revealed a brand-new dual-targeting medication delivery method for the treatment of ovarian cancer. Iron oxide (Fe_3O_4) NPs, produced by the coprecipitation process, comprised the inner core. To link β-CD and single chain antibody (scFv), it was further surface-functionalized with amine groups. At last, docetaxel was added to the grafted β-CD. The sizes of these Fe_3O_4 nanoparticles, both before and after functionalization, were discovered by SEM to be approximately 40 nm. A magnetization test revealed the super-paramagnetic nature of these particles [116]. R. Chalasani's group created photocatalytic Fe_3O_4@TiO_2 core shell MNPs by securing cyclodextrin cavities to the TiO_2 shell; it has been shown that these nanoparticles may absorb and catalytically degrade two endocrine disrupting substances found in water: dibutyl phthalate and bisphenol. After photocatalysis, the functionalized nanoparticles can be magnetically isolated from the dispersion and repurposed. Every element of the Fe_3O_4@TiO_2 core shell nanoparticle functionalized with cyclodextrin plays a vital role in its operation [117].

Concluding remarks

The coprecipitation method is best for synthesizing β-CD-supported MNPs. The coprecipitation method involves the simultaneous precipitation of both the nanoparticles and β-CD in a single step. This simplicity makes the method cost-effective and suitable for large-scale production. By adjusting reaction parameters such as temperature, pH, and precursor concentrations, the coprecipitation method allows for control over the size and morphology of the synthesized nanoparticles. This control is essential for tailoring the properties of the β-CD-supported MNPs to specific applications.

In contrast, while alternative methods *like* thermal decomposition or sol-gel processes may offer higher purity or more controlled nanoparticle sizes under certain conditions, they often require more sophisticated equipment and involve multiple steps, increasing production costs and complexity. Moreover, these methods may not always afford the same level of control over particle size distribution and surface chemistry as the coprecipitation method does.

The choice of β-CD as a support material further influences the properties of MNPs synthesized *via* the coprecipitation method. β-CD's unique cavity structure can accommodate guest molecules, enabling functionalization of MNPs with various biomolecules or therapeutic agents. This functional versatility enhances the MNPs' utility in targeted drug delivery systems and MRI contrast agents, where stability and biocompatibility are critical.

In conclusion, while each synthesis approach has its merits, the coprecipitation method stands out for its simplicity, cost-effectiveness, and ability to tailor nanoparticle properties through straightforward parameter adjustments. When coupled with β-CD as a support material, this method offers a promising route for developing advanced magnetic nanomaterials with tailored functionalities, paving the way for innovative applications in biomedicine and beyond.

3.6 Other support materials

3.6.1 Polymeric materials

Although dendrimers are effective at increasing the number of surface functional groups of polymers and MNPs have additional benefits. Because of their enhanced steric repulsion, they typically need few artificial efforts to reach high molecular weight counterparts, which speeds up the particles' dispersion stabilities. Nevertheless, one intrinsic disadvantage of polymer coatings is that they can hinder access to active areas due to intense polymer diffusion. However, steric crowding may potentially restrict access to active sites in these situations at higher generations (negative dendritic effect). Q.M. Kainz prepared γ-Fe_2O_3 nanocrystals supported on polymer shells [118]. Bin Liu's group created a simple *in situ* distillation–precipitation polymerization process to create Fe_3O_4@polymer microspheres with a distinct core–shell structure, a variety of functional groups that exhibit a saturation magnetization of approximately 54.6 emu·g^{-1} [119], as shown in Figure 7. With this method, there was no surface modification involved; instead, the Fe_3O_4 microspheres that were manufactured were directly covered with a polymer shell through the interaction of hydrogen bonds between the oligomer and the Fe_3O_4 microspheres.

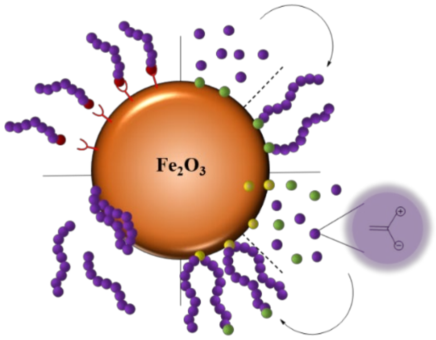


Figure 7. Polymeric materials supported magnetic nanoparticles.

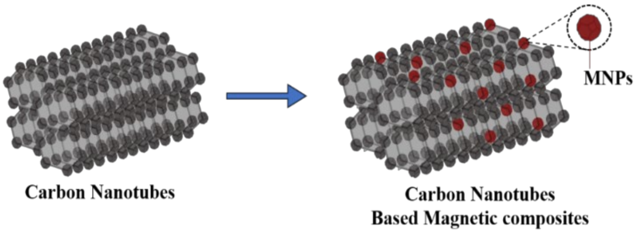


Figure 8. Carbon nanotubes supported magnetic nanoparticles.

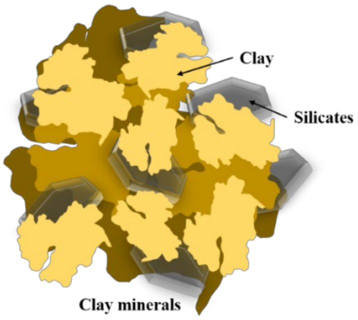


Figure 9. Clay minerals supported magnetic nanoparticles.

3.6.2 Carbon nanotubes

Carbon atoms organized in a hexagonal lattice make up the cylindrical nanostructures known as carbon nanotubes (CNTs). They possess exceptional mechanical strength, electrical conductivity, and thermal conductivity, making them attractive support materials for various applications including catalysis, sensors, and composites [120]. The discovery of carbon nanotubes in 1991 by Sumio Iijima marked a significant milestone in the field of nanotechnology. Since then, researchers have investigated the unique properties of CNTs and explored their potential as support materials for nanoscale systems, as shown in Figure 8. The versatility of CNTs has led to their adoption in diverse fields ranging from electronics to biomedicine. J. Gallego's group offered a process for creating metal nanoparticles covered in graphene that are supported by carbon nanotubes (M-CNTs) to create hybrid, multifunctional materials. The process of impregnation-reduction-decoration (IRD) was used to create these hybrid materials. supported metal nitrates that used CNT to break down and reduce them *in situ*. Following the reduction process, metal particles were encapsulated within a few graphene sheets by treating them with methane pulses at temperatures ranging from 700°C to 900°C. Several analytical methods were used to characterize these hybrid materials [121]. S.K. Folsom's group synthesized nickel-Fe_3O_4 nanoparticles supported on multi-walled carbon nanotubes (Ni-Fe_3O_4/MWCNTs) by mechanically grinding a sample of multi-walled carbon nanotubes (MWCNTs), Fe_3O_4, and nickel salt in a ball-mill mixer. Without the use of a solvent or chemical reagent, the preparation process enables the large-scale manufacture of Ni-Fe_3O_4 NPs at room temperature. The nanoparticles produced using this technique have uniform dispersion of nickel nanoparticles on the surface of multi-walled CNTs and small particle sizes of 5 nm to 8 nm and exhibit a saturation magnetization of approximately 54.6 emu·g^{-1} [122].

3.6.3 Clay minerals

Clay minerals are naturally occurring silicates with layered structures and diverse compositions, as shown in Figure 9. They possess unique properties such as high surface area, cation exchange capacity, and swelling behavior, making them useful as support materials in applications such as ceramics, construction, and environmental remediation [123]. The use of clay minerals dates back thousands of years to ancient civilizations, where they were employed in pottery making and construction. In modern times, researchers have harnessed the properties of clay minerals for various technological applications. Advances in clay mineral synthesis, modification, and characterization have led to their widespread use in diverse industries [124].

G. Zhao's group provided an easy-to-follow process for creating superparamagnetic Fe_3O_4@Clays nanocomposites, which are made up of magnetic iron oxide nanoparticles that have orderly self-assembled on a few specific, confined locations of nano clays. The obtained Fe_3O_4 @Clays have a highly ordered structure, a large surface area, and exhibit a saturation magnetization of approximately 54.24 emu·g^{-1} [125].

K. Kalantari's group produced iron oxide nanoparticles (Fe_3O_4-NPs) developed using chemical coprecipitation. Fe_3O_4-NPs are found as a solid supported at room temperature in the exterior surfaces and interlamellar space of montmorillonite (MMT). One way to adjust the size of magnetite nanoparticles is to alter the amount of reducing agent (NaOH) in the medium. The average diameter of Fe_3O_4 MNPs decreased from 12.88 nm to 8.24 nm, whereas the interlamellar space increased from 1.24 nm to 2.85 nm, and it exhibits a saturation magnetization of approximately 4.56 emu·g^{-1} [126].

As a result of the above discussion, several synthesis techniques have been developed, each with distinct advantages and limitations. For example, coprecipitation offers simplicity and scalability but may result in moderate uniformity, while sol-gel methods provide excellent control over particle morphology at the nanoscale. Hydrothermal synthesis, impregnation, reverse emulsion, in-situ methods, and micro-emulsion techniques each contribute unique characteristics to the final product, tailored to specific application needs.

The choice of support materials such as silica, alumina, cellulose, charcoal, CNTs, and β-CD also plays a crucial role in stabilizing the nanoparticles, enhancing their dispersion, and sometimes contributing to their functional performance. This table summarizes key parameters of MNPs synthesized by various methods, highlighting average particle size, uniformity, magnetic properties, and typical applications.

Table 1 shows trade-offs in supported-magnetic nanoparticle synthesis. Coprecipitation produces 10 nm to 20 nm particles with moderate uniformity and strong magnetism, ideal for drug delivery and remediation, but with less precise size control. Sol-gel yields highly uniform 10 nm to 15 nm particles suited for biomedical uses. Hydrothermal methods create larger, uniform particles (up to 40 nm) for MRI and sensors. Impregnation and reverse emulsion produce small, uniform particles for catalysis and targeted delivery, but with variable magnetic data. In-situ and microemulsion offer easy synthesis and uniformity, with some scalability limits; in-situ methods also support greener approaches.

4. Applications of supported magnetic nanoparticles

4.1 Drug delivery system

The integration of supported magnetic nanoparticles into drug delivery systems holds great potential for advancing personalized medicine, improving treatment outcomes, and addressing unmet medical needs across various disease conditions. Over the past 20 years, there has been a lot of interest in gene therapy as a treatment for hereditary or acquired disorders [127]. Since MNPs are simple to prepare and may have their surface functionalized, they have been studied as nonviral gene delivery vehicles. Recently, a very fascinating assessment of the significance of nanoparticles as delivery mechanisms was released [128]. Cai *et al.* used magnetic CNTs with nickel incorporated in them. When subjected to a magnetic field, these CNTs align with the magnetic flux, striking the cell membrane perpendicularly. The technique known as "nanotube spearing" made it possible to successfully transfer genes into primary B cells and neurons. These synthesized MNPs exhibit a saturation magnetization of approximately 54.6 emu·g^{-1} [129].

S. J. Mattingly *et al.* prepared MNPs-supported lipid bilayers (SLBs), which were then assessed as possible drug carriers. SLBs were built around Fe_3O_4–SiO_2 nanoparticles (SNPs). They explain how combining SNPs with an oxime ether lipid can result in lipid-particle assemblies with extremely favorable potential [130]. The size of supported MNPs used in drug delivery systems can change depending on several factors, including the specific application, desired properties, and synthesis method.

Table 1. Summary of synthesis methods for supported-magnetic nanoparticles.

Method	Support material	p	Uniformity	Magnetic properties	Applications	Source
Coprecipitation	Silica, Alumina, Cellulose, Charcoal, β-CD	10 nm to 20 nm (Fe_3O_4, $CoFe_2O_4$)	Moderate to good	Ms = 42.5 emu·g^{-1} to 93 emu·g^{-1}; Hc = 110 Oe to 2109 Oe	Widely used for drug delivery, catalysis, and environmental remediation	[53–56], [85–88], [116]
Sol-Gel	Silica, Alumina	10 nm to15 nm	High (monodispersed)	Ms = 20.8 emu·g^{-1} to 93 emu/g	Ideal for biomedical applications requiring precise morphology control	[58–60], [72]
Hydrothermal	Alumina, Charcoal	10 nm to 40 nm	High	Ms ≈ 69.5 emu·g^{-1} ($CoFe_2O_4$–graphene sheets)	Suitable for magnetic sensors, MRI, and water treatment	[104], [74]
Impregnation	Silica, Alumina, CNTs	5 nm to12 nm (Rh, Fe, Ni)	Moderate	Variable Ms (not always reported)	Used in heterogeneous catalysis (Ni, Rh), good dispersion with CNTs	[65], [76], [121]
Reverse emulsion	Silica	~10 nm core, 2 nm to 5 nm shell	High (monodispersity)	Ms = 15 emu·g^{-1} to 20 emu·g^{-1}	Precision shell control for drug delivery, imaging	[62–63]
In-situ	Cellulose, Charcoal	~8 nm to 10 nm	Moderate	Not always quantified	Easy synthesis inside biopolymers; used in catalysis, biosensors	[88], [110]
Microemulsion	Charcoal	5 nm to 10 nm	High	Not specified	Good for uniform MNPs; limited by complexity and scalability	[106–107]

4.2 Targeted drug delivery

The inability of medications to function as anticancer agents because they do not reach the tumor tissue promptly is one of the primary challenges in the treatment of cancer. Research has traditionally been focused on getting the medicine directly to the lesion to have the best possible effect. To maximize their potential, magnetic nanoparticles can be surface modified to provide them special qualities and minimal side effects. These particles are thus frequently employed in targeted medicine administration

Hailin Cong *et al.* created an effective way to increase the efficiency of drug release using an IRMOF-3 coated Fe_3O_4@C-based multifunctional NPs that was modified with a targeted ligand (folic acid) and a micro-environmentally responsive separable PEG and exhibit a saturation magnetization of approximately 54.6 $emu{\cdot}g^{-1}$ [131]. Hollow Fe_3O_4/graphene oxide magnetic targeting nanoparticles were employed by J. Wang *et al.* as a medication carrier for tumor-specific therapy. The produced Fe_3O_4/GO has a 5-fluorouracil (5-FU) loading of 0.41 $mg{\cdot}mg^{-1}$, which is positively sensitive to an acidic environment, based on the experimental results [132].

H. Khurshid *et al.* have designed iron oxide magnetic nanoparticles with an average size of 20 nm combined with low-molecular-weight heparin to provide a possible drug delivery method. $FeCl_2$ was reduced by $NaBH_4$ to create the particles, which were subsequently coated with poly-L-lysine. They exhibit a saturation magnetization of approximately 31 $emu{\cdot}g^{-1}$ [133].

Nihal Saad Elbialy *et al.* created magnetic nanoparticles that are nontoxic and suitable for use as a potential nanocarrier for an MTD regimen. Doxorubicin (DOX) was loaded into magnetic gold nanoparticles (MGNPs) after they were synthesized and functionalized with thiol-terminated PEG. The synthesized MNPs exhibit a saturation magnetization of approximately 31 $emu{\cdot}g^{-1}$. A variety of methods were employed to characterize the produced NPs' physical attributes. The produced MGNPs, which have a size of roughly 22 nm, were found to be spherical, monodispersed using TEM [134].

4.3 MRI

Superparamagnetic nanoparticles have special features that make them useful in the biomedical field. As a result, more focus is being paid to the creation and usage of MNPs. When used in targeted tumor diagnostics and treatment, MNPs can significantly enhance both the prognosis and therapeutic outcomes. As MRI reagents, magnetic nanoparticles are utilized in diagnostics. Increasing the stability and biocompatibility of Fe_3O_4 nanoparticles in the application is crucial for optimizing their use in the field of biomedicine and maximizing their performance [135].

According to Hamid Heydari Sheikh Hossein *et al.* the Fe_3O_4@SiO_2@HPG-FA nanoparticles exhibit the best magnetic characteristics and are therefore a good choice as contrast agents for applications involving MRI. The synthesized Fe_3O_4@SiO_2@HPG-FA nanoparticles exhibit a saturation magnetization of approximately 54.6 $emu{\cdot}g^{-1}$ [136].

B. Feng *et al.* produced Fe_3O_4@PEG diacid for MRI using covalent bonding. To create well-dispersed, surface-functionalized, biocompatible MNPs, the surface of Fe_3O_4@PEG NPs was first covered with 3-aminopropyl triethoxysilane (APTES) using a silanization reaction. PEG diacid was then connected to the surface *via* a reaction between $-NH_2$ and $-COOH$. The MNPs were 20 nm in size on average, and at room temperature, they showed high saturation magnetization and superparamagnetism [137].

4.4 Hyperthermia

Thermally responsive nanoparticles have been employed extensively in combination therapy because of their benefits in both hyperthermia attacks and synergistic cancer treatment. It is still difficult to establish a magnetic hyperthermia ablation tumor development technique that works. Now, medication administration, diagnostics, and hyperthermia can all be successfully treated with Fe_3O_4 NPs thanks to their superparamagnetic functionalization system. A. S. Davydov *et al.* focused on the search of materials that combine alternating magnetic field induced heating and high atomic number related dose enhancement abilities. A theoretical evaluation of 24 promising NP compositions was performed: the values of dose enhancement factor were determined for kilovoltage x-ray spectra (30 kVp to 300 kVp), as well as specific absorption rate (SAR) values were calculated for various combinations of elemental compositions and particle size distributions [138].

P. H. Linh *et al.* researched the production of dextran-coated Fe_3O_4 NPs for high-temperature applications and superparamagnetic magnetic fluids with great dispersibility. Canine kidney cells from the Madin Darby strain were used to investigate the magnetic fluid's toxicity in vitro. The outcomes of the experiment demonstrate the magnetic fluid's many potential uses [139].

Izabell Crăciunescu *et al.* synthesized a range of shaped and sized hydrophobic magnetic nanoparticles using a high-temperature reaction between organic precursor solutions to create magnetite (Fe_3O_4) and ferrite (MFe_2O_4, M = Mn, Zn). Sizes and forms ranging from 10 nm to 100 nm were produced, including spherical, cubic, hexagonal, and octahedral configurations. It has been demonstrated that the very high degree of control over the size and form of the surface-coated nanoparticles permits the manipulation of certain characteristics pertinent to numerous possible uses. To increase the MNPs selectivity for treating tumors through hyperthermia, Oihane K [140]. Arriortua *et al.* functionalized Fe_3O_4 NPs using a "click" chemical method and a peptide of the arginine-glycine-aspartate (RGD) type [141].

4.5 Wastewater treatment

Wastewater has a negative impact on human life and productivity. It is impossible to avoid the practical issue of wastewater treatment. Wastewater has been treated using a variety of techniques. However, because of the superior qualities of MNPs, such as their repeatability and magnetism, the application of magnetic nanomaterials for treatment has also drawn attention from researchers [142]. Wenlin Zhang *et al.* produced spherical Fe_3O_4 NPs with a carbon coating (Fe_3O_4@C NPs). Surprisingly, the MNPs exhibit good methylene blue adsorption capacity and can be employed for dye removal in wastewater treatment [143].

Mazyar Sharifzadeh Baei *et al.* [2] developed Fe_3O_4/mordenite to handle greasy wastewater. This process is easy to recycle and quite effective. Petroleum waste can be purified by using it five times in a row. Natálie C. Feitoza *et al.* prepared Glycine-functionalized MNPs for an economical and sustainable alternative to conventional amine-functionalized polymeric coatings for the very effective removal of copper ions from water. Glycine adsorption was studied as a function of ligand concentration and pH after MNPs were created using the coprecipitation method [144].

Ali Akbar Babaei *et al.* treated textile wastewater employing an improved simultaneous adsorption/oxidation method that combines H_2O_2, UV, and ultrasonic (US) radiation with MNPs-functionalized carbon (MNPs@C). The adsorption process involved both pore- and film-diffusion-affected adsorption processes [145]. Xiaoduo Liu *et al.* produced the adsorbent Fe_3O_4 NPs and functionalized activated carbon (Fe_3O_4/AC) to remove methyl orange (MO) and rhodamine B from aqueous solutions quickly and efficiently. The adsorbent's defined physical and chemical characteristics show that it has a high specific surface area, a sensitive magnetic response, and many surfaces functional groups [146].

4.6 Biosensors

Another significant field of study that has received a lot of interest in recent years is biosensing. While unsupported MNPs are typically employed as biosensors for immobilizing and labeling biomolecules (such as DNA), there are instances where SMNPs are used as well. Moreover, SMNPs can be used to improve electron transport between the electrode and biomolecules including proteins and enzymes. Because thick insulating protein shells cover the active centers of enzymes and proteins, they typically do not have direct contact with electrode surfaces. In essence, this stops the two entities' electron transfer cycle. Fe_3O_4 nanoparticle-based bioanalytical sensors can be created by covering Fe_3O_4 NPs with materials *like* polymers, metals, silica, or fluorescent compounds.

Qianqian Zhang *et al.* created a screen-printed carbon electrode with an ordered mesoporous carbon-chitosan/iron oxide chitosan-modified biosensor. Fe_3O_4 and mesoporous carbon improved the electrochemical response [147]. Marcos Eguílaz *et al.* created a novel biosensing electrode surface by combining the benefits of poly(diallyl dimethylammonium chloride) (PDDA)-coated multiwalled carbon nanotubes (MWCNTs) and magnetic ferrite nanoparticles (MNPs) functionalized with glutaraldehyde (GA) as platforms for the development of high-performance multienzyme biosensors [148].

Wenjing Zhang *et al.* created nanocomposites using MNPs and nitrogen-doped graphene (NG) by using an edge-functionalized ball milling technique and then coprecipitation. The generated MNP/NG's catalytic peroxidase-*like* activity is studied. A glucose biosensor confirms the quick identification of H_2O_2 using MNP/NG [149].

4.7 Hydrogenation

In the industrial sector, hydrogenations represent significant shifts where SMNPs have been widely used in recent years. The hydrogenation of methylbenzene by silica-supported Ni-MNPs was shown to be reasonably selective and active, even though the porous silica had a limited surface area. The presence of NiO particles was found to affect the hydrogenation process. Ni-MNPs prepared by the conventional impregnation-reduction route were found to be relatively small (10 nm) and well dispersed on the silica surface, offering interesting activities that were dependent on the preparation thermal pre-treatment step [150].

Fengwei Zhang *et al.* created a palladium-based catalyst supported on amine-functionalized magnetite nanoparticles with ease using a metal adsorption–reduction process in conjunction with a simple one-pot template-free technique. Even at ambient temperature, the catalyst demonstrated rapid conversions for a variety of aromatic nitro and unsaturated compounds, with a turn-over frequency of 83.33 h^{-1} in ethanol under an H_2 environment [151].

4.8 Oxidation

SMNPs' ability to oxidize a variety of substrates has been well studied. The oxidation of CO is the most advanced oxidation process that SMNPs perform. This interest stems from the fact that CO oxidation occurs in fuel cell technology, requiring leftover CO traces to be eliminated from the hydrogen utilized as the fuel source [152].

Maryam Hajjami *et al.* coated Fe_3O_4 MNPs with amino propyl triethoxy silane to enable selective oxidation of sulfides to sulfoxides with recoverable catalysis. Then, the nanoparticles interacted with isatin to form imine-bonded Fe_3O_4 NPs. $ZrOCl_2{\cdot}8H_2O$ or $CuCl_2$ were added, and novel magnetically separable catalysts, Zr(IV)/isatin@Fe_3O_4 or Cu (II)/isatin@Fe_3O_4, were formed [153].

Fatemeh Rajabi *et al.* outlined a straightforward, effective, and eco-friendly room temperature aqueous catalytic method that uses aqueous hydrogen peroxide as an oxidant and low-loaded supported iron oxide nanoparticles to selectively prepare sulfoxides from sulfides. There was no metal leaching throughout the reaction, and materials could be readily collected from the reaction mixture and reused 10 time without losing activity. Thus, this is the first time that sulfides have been selectively oxidized in water utilizing a heterogeneous system based on iron [154].

Sajjad Keshipour *et al.* coated palladium and Fe_3O_4 NPs with N-(2-aminoethyl) acetamide-functionalized cellulose for application in a catalytic process. The catalyst was used in the oxidation process of ethylbenzene at 100°C using H_2O_2. It was studied by Fourier transform infrared spectroscopy, thermogravimetric analysis, X-ray diffraction, energy-dispersive X-ray analysis, and transmission electron microscopy. The only byproduct of the 24 h oxidation process was styrene oxide [88].

5. Future prospects and challenges

Supported MNPs have emerged as versatile materials with promising prospects across various fields due to their unique properties and wide-ranging applications [155]. The integration of MNPs with support materials such as silica, alumina, cellulose, charcoal, polymer materials, and clay minerals enhances their stability, dispersibility, and functionality, thereby expanding their utility. In biomedicine, supported MNPs hold immense potential for targeted drug delivery, magnetic hyperthermia cancer treatment, and MRI contrast enhancement [156].

Moreover, their magnetic properties facilitate selective heating of tumor tissues under alternating magnetic fields, offering a non-invasive approach for cancer therapy. In environmental remediation, supported magnetic nanoparticles play a pivotal role in pollutant removal and wastewater treatment. By exploiting the high surface area and adsorption capacity of support materials, these nanocomposites efficiently capture heavy metals, organic pollutants, and emerging contaminants from aqueous solutions [157].

In catalysis, supported MNPs serve as efficient catalysts for various chemical transformations, including organic synthesis, pollutant degradation, and renewable energy conversion [158]. The synergistic effects between the magnetic cores and support materials enhance catalytic activity, selectivity, and recyclability. Functionalized support materials enable immobilization of recognition elements, facilitating specific molecular recognition and signal transduction [159].

This review explores recent advancements in the synthesis, coating, functionalization, and applications of MNPs, which have seen significant growth and diversification in recent decades. MNPs have proven versatile across various fields, serving as effective photocatalysts, catalytic supports, electrode materials, and adsorbents. Moreover, their biomedical applications have rapidly expanded from drug delivery systems to high-performance separation processes integrated into microfluidic systems for diagnostics and disease management. The evolution of MNP applications owes much to advances in synthesis methods and surface modification techniques. Particularly noteworthy is the increasing integration of these processes into microfluidic devices, which offer enhanced control and safety. Microfluidics enables the production of MNPs with smaller sizes and narrower size distributions, crucial for improving their performance in diverse applications [19].

While supported magnetic nanoparticles have shown tremendous potential across biomedical, environmental, and catalytic domains, several challenges remain. Key issues include the reproducibility and scalability of synthesis methods, especially when precise control over particle size and morphology is required. The long-term stability of SMNPs under varying environmental or physiological conditions is also a concern, particularly for in vivo applications. Additionally, surface functionalization often involves complex multi-step procedures that can affect biocompatibility or magnetic performance. Regulatory and toxicity considerations for clinical or environmental use further complicate translation to practical applications. Future efforts should focus on developing green, scalable synthesis routes; enhancing the robustness and specificity of surface functionalization; and improving regulatory frameworks to facilitate safe deployment. Addressing these challenges will be essential to fully realize the interdisciplinary impact of supported MNPs.

6. Conclusion

In summary, supported MNPs represent a dynamic field with immense potential. They have emerged as versatile materials with wide-ranging applications due to their unique properties and ease of manipulation. By judiciously integrating MNPs into diverse support materials, researchers achieve multifunctionality and enhanced performance. These support matrices provide stability, preventing aggregation and thereby preventing aggregation and facilitating better control over their properties. Additionally, the combination of MNPs with different support materials offers tailored surface chemistries and functionalities, expanding their utility in fields such as catalysis, biomedical applications, environmental remediation, and magnetic separation techniques. The synergistic effects between the MNPs and support materials further enhance their stability, reusability, and overall performance, making them promising candidates for a wide array of technological advancements. Notably, the interplay between nano magnetism and support characteristics significantly influences MNP behaviour.

Authors contributions

Investigation, N.K., & M.K.; Writing—original draft, K., N.K. & A.K.N.; Writing—review & editing, K., H.S., and M.V.; Supervision, M.K. and H.S.S. All authors have read and agreed to the published version of the manuscript.

References

[1] P. Minakshi, M. Ghosh, B. Brar, K. Ranjan, H. S. Patki, and R. Kumar, "Separation techniques with nanomaterials," in *Handbook of Nanomaterials in Analytical Chemistry: Modern Trends in Analysis*, pp. 99–158, 2020.

[2] N. Sezer, İ. Arı, Y. Biçer, and M. Koç, "Superparamagnetic nanoarchitectures: Multimodal functionalities and applications," *Journal of Magnetism and Magnetic Materials*, vol. 538, p. 168300, 2021.

[3] S. Singamaneni, V. N. Bliznyuk, and C. Binek, "Magnetic nanoparticles: Recent advances in synthesis, self-assembly and applications," *Journal of Materials Chemistry*, vol. 21, no. 42, pp. 16819–16845, 2011.

[4] B. Thiesen, and A. Jordan, "Clinical applications of magnetic nanoparticles for hyperthermia," *International Journal of Hyperthermia*, vol. 24, no. 6, pp. 467–474, 2008,.

[5] S. S. Leong, Z. Ahmad, S. C. Low. J. Camacho, J. Faraudo, and J. Lim, "Unified view on magnetic nanoparticle separation under magnetophoresis," Langmuir, vol. 36, no. 28, pp. 8033–8055, 2020.

[6] R. Brüning, L. Rózsa, R. Lo Conte, A. Kubetzka, R. Wiesendanger, and K. von Bergmann, "Topological meron-antimeron domain walls and skyrmions in a low-symmetry system," *Physical Review Journals,* vol. 15, no. 2, p. 21041, 2025.

[7] L. V. Dieren, A. A. Ruzette, V. Tereshenko, H. Oubari, Y. Berkane, J. Cornacchini, F. Thiessen, C. L. Cetrulo, K. Uygun, and A. G. Lellouch, "Computational modeling of superparamagnetic nanoparticle-based (affinity) diagnostics.," *Frontiers in Bioengineering and Biotechnology*, vol. 12, no. 1, p. 1500756, 2024.

[8] A. G. Kolhatkar, A. C. Jamison, D. Litvinov, R. C. Willson, and T. R. Lee, "Tuning the magnetic properties of nanoparticles," *International journal of molecular sciences*, vol. 14, no. 8, pp. 15977–16009, 2013.

[9] K. Parekh, and N. Jain, "Toxicology of Superparamagnetic Materials," *in book Superparamagnetic Materials for Cancer Medicine*, 2023, pp. 199–217.

[10] S. Schuerle, S. Erni, M. Flink, B. E. Kratochvil, and B. Nelson, "Three-dimensional magnetic manipulation of micro-and nanostructures for applications in life sciences," *IEEE Transactions on Magnetics*, vol. 49, no. 1, pp. 321–330, 2013.

[11] J. F. Liu , B. Jang, D. Issadore, and A. Tsourkas, "Use of magnetic fields and nanoparticles to trigger drug release and improve tumor targeting," *WIREs Nanomedicine and Nanobiotechnology*, vol. 11, no. 6, p. e1571, 2019.

[12] J. Huang, X. Zhong, L. Wang, L. Yang, Lily, and H. Mao, "Improving the magnetic resonance imaging contrast and detection methods with engineered magnetic nanoparticles," Theranostics, vol. 2, no. 1, pp. 86–102, 2012.

[13] D. Yoo, J.-H. Lee, T.-H. Shin, and J. Cheon, "Theranostic magnetic nanoparticles," *Accounts of Chemical Research*, vol. 44, no. 10, pp. 863–874, 2011.

[14] Y.-L. Liu, D. Chen, P. Shang, and D.-C. Yin, "A review of magnet systems for targeted drug delivery," *Journal of Controlled Release*, vol. 302, pp. 90–104, 2019.

[15] S. Sun, and H. Zeng, "Size-controlled synthesis of magnetite nanoparticles," *Journal of the American Chemical Society*, vol. 124, no. 28, pp. 8204–8205, 2002.

[16] Y. Bao, T. Wen, A. C. S. Samia, A. Khandhar, and K. M. Krishnan, "Magnetic nanoparticles: material engineering and emerging applications in lithography and biomedicine," *Journal of materials science*, vol. 51, no. 1, pp. 513–553, 2015.

[17] M. M. Selim, S. El-safty, A. Tounsi, and M. Shenashen, "A review of magnetic nanoparticles used in nanomedicine," *APL Materials*, vol. 12, no. 1, pp. 1–14, 2024.

[18] G. F. Stiufiuc, and R. Stiufiuc, "Magnetic nanoparticles: synthesis, characterization, and their use in biomedical field," *Applied Sciences*, vol. 14, no. 4, p. 1623, 2024.

[19] V. F. Cardoso, A. Francesko, C. Ribeiro, M. Bañobre-López, P. Martins, and S. Lanceros-Mendez, "Advances in magnetic nanoparticles for biomedical applications," *Advanced Healthcare Materials*, vol. 7, no. 5, p. 1700845, 2017.

[20] D. Wang, and D. Astruc, "Fast-growing field of magnetically recyclable nanocatalysts," *Chemical Reviews*, vol. 114, no. 14, pp. 6949–6985, 2014.

[21] A. D. Eren A, "Model-based design of pharmaceutical crystallization processes," Ph.D. dissertation, Department of Chemical Engineering, Purdue University, West Lafayette, Indiana, United States 2021.

[22] L. Guerrini, R. A. Alvarez-Puebla, and N. Pazos-Perez, "Surface modifications of nanoparticles for stability in biological fluids," *Materials*, vol. 11, no. 7, p. 1154, 2018.

[23] S. Wan, J. Peng, L. Jiang, and Q. Cheng, "Bioinspired graphene-based nanocomposites and their application in flexible energy devices," *Advanced Materials*, vol. 28, no. 36, pp. 7862–7898, 2016.

[24] P. M. Martins, A. C. Lima, S. Ribeiro, S. Lanceros-Mendez, and P. Martins, "Magnetic nanoparticles for biomedical applications: From the soul of the earth to the deep history of ourselves," *ACS Applied Bio Materials*, vol. 4, no. 8, pp. 5839-5870, 2021.

[25] R. A. Sheldon, I. W. C. E. Arends, and U. Hanefeld, *Green chemistry and catalysis*, Wiley-VCH Verlag GmbH; 1st edition, Wiley-VCH, 2007, pp. 1–448

[26] X. Mao, J. Xu, and H. Cui, "Functional nanoparticles for magnetic resonance imaging," *Wiley Interdiscip Rev Nanomed Nanobiotechnol*, vol. 8, no. 6, pp. 814-841, 2016.

[27] M. A. M. Gijs, F. Lacharme, and U. Lehmann, "Microfluidic applications of magnetic particles for biological analysis and catalysis," *Chemical Reviews*, vol. 110, no. 3, pp. 1518–1563, 2010.

[28] P. Mondal, A. Anweshan, and M. K. Purkait, "Green synthesis and environmental application of iron-based nanomaterials and nanocomposite: A review," *Chemosphere*, vol. 259, p. 127509, 2020.

[29] M. D. Nguyen, H.-V. Tran, S. Xu, and T. R. Lee, "Fe_3O_4 nanoparticles: Structures, synthesis, magnetic properties, surface functionalization, and emerging applications," *Applied Sciences*, vol. 11, no. 23, pp. 1–22, 2021.

[30] K. T. Turcheniuk, A. V. Tarasevych, V. P. Kukhar, R. Boukherroub, and S. Szunerits, "Recent advances in surface chemistry strategies for the fabrication of functional iron oxide based magnetic nanoparticles," *Nanoscale*, vol. 5, no. 22, pp. 10729–10752, 2013.

[31] Y.-W. Lee, H. Ceylan, I. C. Yasa, U. Kilic, and M. Sitti, "3D-printed multi-stimuli-responsive mobile micromachines," *ACS Applied Materials & Interfaces*, vol. 13, no. 11, pp. 12759-12766, 2021.

[32] S. Shrestha, B. Wang, and P. Dutta, "Nanoparticle processing: Understanding and controlling aggregation," *Advances in Colloid and Interface Science*, vol. 279, p. 102162, 2020.

[33] J. Kudr, Y. Haddad, L. Richtera, Z. Heger, M. Cernak, V. Adam, and O. Zitka, "Magnetic nanoparticles: From design and synthesis to real world applications," *Nanamaterials*, vol. 7, no. 9, p. 243, 2017.

[34] A.-H. Lu, E. L. Salabas, and F. Schüth, "Magnetic nanoparticles: Synthesis, protection, functionalization, and application," *Angewandte Chemie International Edition*, vol. 46, no. 8, pp. 1222-1244, 2007.

[35] D. D. V. Stueber , J. Villanova, I. Aponte, Z. Xiao, and V. L. Colvin, "Magnetic nanoparticles in biology and medicine: Past, present, and future trends," *Pharmaceutics*, vol. 13, no. 7, p. 943, 2021.

[36] J. G. Croissant, Y. Fatieiev, A. Almalik, and N. M. Khashab, "Mesoporous silica and organosilica nanoparticles: Physical chemistry, biosafety, delivery strategies, and biomedical applications," *Advanced Healthcare Materials*, vol. 7, no. 4, p. 1700831, 2017.

[37] R. A. Bohara, N. D. Thorat, and S. H. Pawar, "Role of functionalization: Strategies to explore potential nano-bio applications of magnetic nanoparticles," *RSC Advances*, vol. 6, no. 50, pp. 43989-44012, 2016.

[38] Y. Cao, Y. Yuan, Y. Shang, V. I. Zverev, R. R. Gimaev, R. Barua, R. L. Hadimani, L. Mei, G. Guo, and H. Fu, "Phase transition and magnetocaloric effect in particulate Fe-Rh alloys," *Journal of Materials Science*, vol. 55, no. 27, pp. 13363–13371, 2020.

[39] Y. Lin, K. Zhang, R. Zhang, Z. She, R. Tan, Y. Fan, and X. Li, "Magnetic nanoparticles applied in targeted therapy and magnetic resonance imaging: Crucial preparation parameters, indispensable pre-treatments, updated research advancements and future perspectives," *Journal of Materials Chemistry B*, vol. 8, no. 28, pp. 5973–5991, 2020.

[40] J. Trujillo-Reyes, J. R. Peralta-Videa, and J. L. Gardea-Torresdey, "Supported and unsupported nanomaterials for water and soil

remediation: Are they a useful solution for worldwide pollution?," *Journal of Hazardous Materials*, vol. 280, pp. 487–503, 2014.

[41] J. Theerthagiri, S. J. Lee, K. Karuppasamy, S. Arulmani, S. Veeralakshmi, M. Ashokkumar, and M. Y. Choi, "Application of advanced materials in sonophotocatalytic processes for the remediation of environmental pollutants," *Journal of Hazardous Materials*, vol. 412, p. 125245, 2021.

[42] F. Varíola, F. Vetrone, L. Richert, P. Jedrzejowski, J.-H. Yi, S. Zalzal, S. Clair, A. Sarkissian, D. F. Perepichka, J. D. Wuest, F. Rosei, and A. Nanci, "Improving biocompatibility of implantable metals by nanoscale modification of surfaces: An overview of strategies, fabrication methods, and challenges," *Small*, vol. 5, no. 9, pp. 996–1006, 2009.

[43] R. Potyrailo, K. Rajan, K. Stoewe, I. Takeuchi, B. Chisholm, and H. Lam, "Combinatorial and high-throughput screening of materials libraries: Review of state of the art," *ACS Combinatorial Science*, vol. 13, no. 6, pp. 579-633, 2011.

[44] J. R. Vargas-Ortiz, C. Gonzalez, and K. Esquivel, "Magnetic iron nanoparticles: Synthesis, surface enhancements, and biological challenges," *Processes*, vol. 10, no. 11, pp. 2282–2320, 2022.

[45] C. Nwabunwanne, S. O. Aisida, R. Javed, K. G. Akpomie, C. Awada, A. Alshoaibi, and F. Ezema, "Magnetic nanoparticles: Biosynthesis, characterization, surface functionalization and biomedical applications," *Journal of the Indian Chemical Society*, vol. 102, no. 3, p. 101617, 2025.

[46] J. Wallyn, N. Anton, and T. F. Vandamme, "Synthesis, principles, and properties of magnetite nanoparticles for in vivo imaging applications—A review," *Pharmaceutics*, vol. 11, no. 11, pp. 1–29, 2019.

[47] K. Zhu, Y. Ju, J. Xu, Z. Yang, S. Gao, and Y. Hou, "Magnetic nanomaterials: Chemical design, synthesis, and potential applications," *Accounts of Chemical Research*, vol. 51, no. 2, pp. 404–413, 2018.

[48] F. Mahtab, Y. Yu, J. W. Y. Lam, J. Liu, B. Zhang, P. Lu, X. Zhang, and B. Z. Tang, "Fabrication of silica nanoparticles with both efficient fluorescence and strong magnetization, and exploration of their biological applications," *Advanced Functional Materials,* vol. 21, no. 9, pp. 1733–1740, 2011.

[49] R. K. Kankala, H. Zhang, C.-G. Liu, K. R. Kanubaddi, C.-H. Lee, S.-B. Wang, W. Cui, H. A. Santos, K. Lin, and A.-Z. Chen, "Metal species–encapsulated mesoporous silica nanoparticles: current advancements and latest breakthroughs," *Advanced Functional Materials,* vol. 29, no. 43, p. 1902652, 2019.

[50] D. K. Yi, S. T. Selvan, S. S. Lee, G. C. Papaefthymiou, D. Kundaliya, and J. Y. Ying, "Silica-coated nanocomposites of magnetic nanoparticles and quantum dots," *Journal of the American Chemical Society* vol. 127, no. 14, pp. 4990–4991, 2005.

[51] N. Joudeh, and D. Linke, "Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists," *Journal of Nanobiotechnology*, vol. 20, no. 1, pp. 1–29, 2022.

[52] A. Rimola, D. Costa, M. Sodupe, J.-F. Lambert, and P. Ugliengo, "Silica surface features and their role in the adsorption of biomolecules: Computational modeling and experiments," *Chemical Reviews*, vol. 113, no. 6, pp. 4216–4313, 2013.

[53] S. Wang, Z. Zhang, B. Liu, and J. Li, "Silica coated magnetic Fe_3O_4 nanoparticles supported phosphotungstic acid: a novel environment-friendly catalyst for the synthesis of 5-ethoxymethylfurfural from 5-hydroxymethylfurfural and fructose," *Catalysis Science & Technology*, vol. 3, no. 8, pp. 2104–2112, 2013.

[54] D. V. Quy, N. M. Hieu, P. T. Tra, N. H. Nam, N. H. Hai, N. T. Son, P. T. Nghia, N. T. V. Anh, T. T. Hong, and N. H. Luong, "Synthesis of silica-coated magnetic nanoparticles and application in the detection of pathogenic viruses," *Journal of Nanomaterials*, vol. 2013, no. 1, pp. 1–7, 2013.

[55] G. Aygar, M. Kaya, N. Özkan, S. Kocabiyik, and M. Volkan, "Preparation of silica coated cobalt ferrite magnetic nanoparticles for the purification of histidine-tagged proteins," *Journal of Physics and Chemistry of Solids*, vol. 87, pp. 64–71, 2015.

[56] N. Mahmed, O. Heczko, A. Lancok, and S.-P. Hannula, "The magnetic and oxidation behavior of bare and silica-coated iron oxide nanoparticles synthesized by reverse co-precipitation of ferrous ion (Fe^{2+}) in ambient atmosphere," *Journal of Magnetism and Magnetic Materials*, vol. 353, pp. 15–22, 2014.

[57] N. Pal, J. H. Lee, and E. B. Cho, "Recent trends in morphology-controlled synthesis and application of mesoporous silica nanoparticles," Nanomaterials, vol. 10, no. 11, p. 2122, 2020.

[58] E. Ranjbakhsh, A. K. Bordbar, M. Abbasi, A. R. Khosropour, and E. Shams, "Enhancement of stability and catalytic activity of immobilized lipase on silica-coated modified magnetite nanoparticles," *Chemical Engineering Journal*, vol. 179, pp. 272–276, 2012.

[59] Y.-H. Deng, C.-C. Wang, J.-H. Hu, W.-L. Yang, and S.-K. Fu, "Investigation of formation of silica-coated magnetite nanoparticles *via* sol-gel approach," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 262, no. 1–3, pp. 87–93, 2005.

[60] C. Jin, Y. Wang, H. Wei, H. Tang, X. Liu, T. Lu, and J. Wang, "Magnetic iron oxide nanoparticles coated by hierarchically structured silica: A highly stable nanocomposite system and ideal catalyst support," *Journal of Materials Chemistry A*, vol. 2, no. 29, pp. 11202–11208, 2014.

[61] F. Venditti, R. Angelico, G. Palazzo, G. Colafemmina, A. Ceglie, and F. Lopez, "Preparation of nanosize silica in reverse micelles: Ethanol produced during TEOS hydrolysis affects the microemulsion structure," *Langmuir*, vol. 23, no. 20, pp. 10063–10068, 2007.

[62] M. Zhang, B. L. Cushing, and C. J. O'Connor, "Synthesis and characterization of monodisperse ultra-thin silica-coated magnetic nanoparticles," *Nanotechnology*, vol. 19, no. 8, p. 85601, 2008.

[63] I. Rhee, T. Ahmad, S. Hong, Y. Chang, and J. Lee, "Silica-coated iron-oxide nanoparticles synthesized as a T2 contrast agent for magnetic resonance imaging by using the reverse micelle method," *Journal- Korean Physical Society*, vol. 57, no. 6, pp. 1545–1549, 2010.

[64] T. M. Eggenhuisen, M. J. Van Steenbergen, H. Talsma, P. E. de Jongh, and K. P. de Jong, "Impregnation of mesoporous silica for catalyst preparation studied with differential scanning calorimetry," *The Journal of Physical Chemistry C*, vol. 113, no. 38, pp. 16785–16791, 2009.

[65] V. Mévellec, A. Nowicki, A. Roucoux, C. Dujardin, P. Granger, E. Payen, and K. Philippot, "A simple and reproducible method for the synthesis of silica-supported rhodium nanoparticles and their investigation in the hydrogenation of aromatic compounds," *New Journal of Chemistry,* vol. 30, no. 8, pp. 1214–1219, 2006.

[66] K. Chaiseeda, S. Nishimura, and K. Ebitani, "Gold nanoparticles supported on alumina as a catalyst for surface plasmon-enhanced selective reductions of nitrobenzene," *ACS Omega*, vol. 2, no. 10, pp. 7066–7070, 2017.

[67] P. Riani, G. Garbarino, M. A. Lucchini, F. Canepa, G. Busca, "Unsupported versus alumina-supported Ni nanoparticles as catalysts for steam/ethanol conversion and CO_2 methanation," *Journal of Molecular Catalysis A: Chemical,* vol. 383–384, pp. 10–16, 2014.

[68] L. M. Rossi, N. J. S. Costa, F. P. Silva, and R. Wojcieszak, "Magnetic nanomaterials in catalysis: Advanced catalysts for magnetic separation and beyond," *Green Chemistry*, vol. 16, no. 6, pp. 2906-2933, 2014.

[69] M. B. Gawande, A. Goswami, F.-X. Felpin, T. Asefa, X. Huang, R. Silva, X. Zou, R. Zboril, and R. S. Varma, "Cu and Cu-based nanoparticles: synthesis and applications in catalysis," *Chemical Reviews*, vol. 116, no. 6, pp. 3722–3811, 2016.

[70] L. Sun, C. Zhang, L. Chen, J. Liu, H. Jin, H. Xu, and L. Ding, "Preparation of alumina-coated magnetite nanoparticle for extraction of trimethoprim from environmental water samples based on mixed hemimicelles solid-phase extraction," *Analytica Chimica Acta*, vol. 638, no. 2, pp. 162–168, 2009.

[71] D. Karabelli, S. Ünal, T. Shahwan, and A. E. Eroĝlu, "Preparation and characterization of alumina-supported iron nanoparticles and its application for the removal of aqueous Cu^{2+} ions," *Chemical Engineering Journal*, vol. 168, no. 2, pp. 979–984, 2011.

[72] C. Marichy, M. Bechelany, and N. Pinna, "Atomic layer deposition of nanostructured materials for energy and environmental applications," *Advanced Materials*, vol. 24, no. 8, pp. 1017–1032, 2012.

[73] Z. Yao, Y. Peng, C. Xia, X. Yi, S. Mao, and M. Zhang, "The effect of calcination temperature on microstructure and properties of FeNiMo@Al_2O_3 soft magnetic composites prepared by sol-gel method," *Journal of Alloys and Compounds*, vol. 827, p. 154345, 2020

[74] S. Said, S. Mikhail, and M. Riad, "Recent processes for the production of alumina nano-particles," *Materials Science for Energy Technologies*, vol. 3, pp. 344–363, 2020.

[75] S. Ghanizadeh, X. Bao, B. Vaidhyanathan, and J. Binner, "Synthesis of nano α-alumina powders using hydrothermal and precipitation routes: A comparative study," *Ceramics International*, vol. 40, no. 1 Part B, pp. 1311–1319, 2014.

[76] P. Munnik, P. E. de Jongh, and K. P. de Jong, "Recent developments in the synthesis of supported catalysts," *Chemical Reviews*, vol. 115, no. 14, pp. 6687–6718, 2015.

[77] J.-Y. Park, Y.-J. Lee, P. K. Khanna, K.-W. Jun, J. W. Bae, and Y. H. Kim, "Alumina-supported iron oxide nanoparticles as Fischer-Tropsch catalysts: Effect of particle size of iron oxide," *Journal of Molecular Catalysis A: Chemical*, vol. 323, no. 1–2, pp. 84–90, 2010.

[78] X. Wu, Z. Shi, S. Fu, J. Chen, R. M. Berry, and K. C. Tam, "Strategy for synthesizing porous cellulose nanocrystal supported metal nanocatalysts," *ACS Sustainable Chemistry & Engineering*, vol. 4, no. 11, pp. 5929–5935, 2016.

[79] G. Biliuta, and S. Coseri, "Cellulose: A ubiquitous platform for ecofriendly metal nanoparticles preparation," *Coordination Chemistry Reviews*, vol. 383, pp. 155–173, 2019.

[80] K. B. R. Teodoro, R. C. Sanfelice, F. L. Migliorini, A. Pavinatto, M. H. M. Facure, and D. S. Correa, "A Review on the role and performance of cellulose nanomaterials in sensors," *ACS Sensors*, vol. 6, no. 7, pp. 2473–2496, 2021.

[81] M. A. C. M. Haniffa, K. Munawar, C. Y. Chee, S. Pramanik, A. Halilu, H. A. Illias, M. Rizwan, R. Senthilnithy, K. R. R. Mahanama, A. Tripathy, and M. F. Azman, "Cellulose supported magnetic nanohybrids: Synthesis, physicomagnetic properties and biomedical applications-A review," *Carbohydrate Polymers*, vol. 267, p. 118136, 2021.

[82] K. Petcharoen, and A. Sirivat, "Synthesis and characterization of magnetite nanoparticles *via* the chemical co-precipitation method," *Materials Science and Engineering: B*, vol. 177, no. 5, pp. 421–427, 2012.

[83] Z. Zhao, J. Tian, Y. Sang, A. Cabot, and H. Liu, "Structure, synthesis, and applications of TiO_2 nanobelts," *Advanced Materials*, vol. 27, no. 16, pp. 2557–2582, 2015.

[84] Q. Zhang, J. Li, H. Miao, and J. Fu, "Preparation of γ-Fe_2O_3 /Ni_2O_3/$FeCl_3$($FeCl_2$) composite nanoparticles by hydrothermal process useful for ferrofluids," *Smart Materials Research*, vol. 2011, pp. 1–5, 2011.

[85] J. Zhang, X. Feng, J. Wang, G. Fang, J. Liu, and S. Wang, "Nano-crystalline cellulose-coated magnetic nanoparticles for affinity adsorption of glycoproteins," *Analyst*, vol. 145, no. 9, pp. 3407–3413, 2020.

[86] C. Wan, and J. Li, "Synthesis of well-dispersed magnetic $CoFe_2O_4$ nanoparticles in cellulose aerogels *via* a facile oxidative co-precipitation method," *Carbohydrate Polymers*, vol. 134, pp. 144–150, 2015.

[87] T. Pasinszki, and M. Krebsz, "Synthesis and application of zero-valent iron nanoparticles in water treatment, environmental remediation, catalysis, and their biological effects," *Nanomaterials*, vol. 10, no. 5, p. 917, 2020.

[88] S. Keshipour, and N. K. Khalteh, "Oxidation of ethylbenzene to styrene oxide in the presence of cellulose-supported Pd magnetic nanoparticles," *Applied Organometallic Chemistry*, vol. 30, no. 8, pp. 653–656, 2016.

[89] A. Barhoum, J. Jeevanandam, A. Rastogi, P. Samyn, A. Dufresne, M. K. Danquah, and M. Bechelany, "Plant celluloses, hemicelluloses, lignins, and volatile oils for the synthesis of nanoparticles and nanostructured materials," *Nanoscale*, vol. 12, no. 45, pp. 22845–22890, 2020.

[90] H. N. Abdelhamid, and A. P. Mathew, "Cellulose-based nanomaterials advance biomedicine: A Review," *International Journal of Molecular Sciences,* vol. 23, no. 10, p. 5405, 2022.

[91] B. Mohan, J. C. Park, and K. H. Park, "Mechanochemical synthesis of active magnetite nanoparticles supported on charcoal for facile synthesis of alkynyl selenides by C−H activation," *ChemCatChem*, vol. 8, no. 14, pp. 2345–2350, 2016.

[92] M. I. Anik, M. K. Hossain, I. Hossain, A. M. U. B. Mahfuz, M. T. Rahman, and I. Ahmed, "Recent progress of magnetic nanoparticles in biomedical applications: A review," *Nano Select*, vol. 2, no. 6, pp. 1146–1186, 2021.

[93] S. Mahdavi, M. Jalali, and A. Afkhami, "Removal of heavy metals from aqueous solutions using Fe_3O_4, ZnO, and CuO nanoparticles," *Journal of Nanoparticle Research*, vol. 14, no. 8, 2012.

[94] G. R. Surup, A. Trubetskaya, and M. Tangstad, "Charcoal as an alternative reductant in ferroalloy production: A review," *Processes*, vol. 8, no. 11, pp. 1–41, 2020.

[95] K. P. Keboletse, F. Ntuli, and O. P. Oladijo, "Influence of coal properties on coal conversion processes-coal carbonization, carbon fiber production, gasification and liquefaction technologies: A review," *International Journal of Coal Science & Technology,* vol. 8, no. 5, pp. 817–843, 2021.

[96] A. Singh, J. Dhau, R. Kumar, R. Badru, P. Singh, Y. K. Mishra, and A. Kaushik, "Tailored carbon materials (TCM) for enhancing photocatalytic degradation of polyaromatic hydrocarbons," *Progress in Materials Science*, vol. 144, p. 101289, 2024.

[97] A. Mahor, P. P. Singh, P. Bharadwaj, N. Sharma, S. Yadav, J. M. Rosenholm, and K. K. Bansal, "Carbon-based nanomaterials for delivery of biologicals and therapeutics: A cutting-edge technology," *C*, vol. 7, no. 1, p. 19, 2021.

[98] S. Laurent, D. Forge, M. Port, A. Roch, C. Robic, L. V. Elst, and R. N. Muller, "Magnetic iron oxide nanoparticles: Synthesis, stabilization, vectorization, physicochemical characterizations and biological applications," *Chemical Reviews*, vol. 108, no. 6, pp. 2064–2110, 2008.

[99] N. Yang, S. Zhu, D. Zhang, and S. Xu, "Synthesis and properties of magnetic Fe_3O_4-activated carbon nanocomposite particles for dye removal," *Materials Letters*, vol. 62, no. 4–5, pp. 645–647, 2008.

[100] L. M. Martínez-Prieto, J. Marbaix, J. M. Asensio, C. Cerezo-Navarrete, P.-F. Fazzini, K. Soulantica, B. Chaudret, and A. Corma, "Ultrastable magnetic nanoparticles encapsulated in carbon for magnetically induced catalysis," *ACS Applied Nano Materials*, vol. 3, no. 7, pp. 7076–7087, 2020.

[101] J. Wan, H. Deng, J. Shi, L. Zhou, and T. Su, "Synthesized magnetic manganese ferrite nanoparticles on activated carbon for sulfamethoxazole removal," *Clean - Soil, Air, Water*, vol. 42, no. 9, pp. 1199–1207, 2014.

[102] W. Wu, Z. Wu, T. Yu, C. Jiang, and W.-S. Kim, "Recent progress on magnetic iron oxide nanoparticles: Synthesis, surface functional strategies and biomedical applications," *Science and Technology of Advanced Materials*, vol. 16, no. 2, 2015.

[103] N. T. K. Thanh, N. Maclean, and S. Mahiddine, "Mechanisms of nucleation and growth of nanoparticles in solution," *Chemical Reviews*, vol. 114, no. 15, pp. 7610–7630, 2014.

[104] N. Li, M. Zheng, X. Chang, G. Ji, H. Lu, L. Xue, L. Pan, and J. Cao, "Preparation of magnetic $CoFe_2O_4$-functionalized graphene sheets *via* a facile hydrothermal method and their adsorption properties," *Journal of Solid State Chemistry*, vol. 184, no. 4, pp. 953–958, 2011.

[105] Y.-H. Cho, S. Kim, E. K. Bae, C. K. Mok, and J. Park, "Formulation of a cosurfactant-free O/W microemulsion using nonionic surfactant mixtures," *Journal of Food Science,* vol. 73, no. 3, pp. E115-E121, 2008.

[106] I. Fatimah, G. Fadillah, and S. P. Yudha, "Synthesis of iron-based magnetic nanocomposites: A review," *Arabian Journal of Chemistry*, vol. 14, no. 8. p. 103301, 2021.

[107] W. Yu, and H. Xie, "A review on nanofluids: Preparation, stability mechanisms, and applications," *Journal of Nanomaterials*, vol. 2012, no. 1, p. 435873, 2012.

[108] A. M. El Shafey, "Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review," *Green Processing and Synthesis*, vol. 9, no. 1, pp. 304–339, 2020.

[109] A. V. Rane, K. Kanny, V. K. Abitha, and S. Thomas, "Methods for synthesis of nanoparticles and fabrication of nanocomposites," *Synthesis of Inorganic Nanomaterials: Advances and Key Technologies*, pp. 121–139, 2018.

[110] Y. Zhang, G.-M. Zeng, L. Tang, D.-L. Huang, X.-Y. Jiang, and Y.-N. Chen, "A hydroquinone biosensor using modified core-shell magnetic nanoparticles supported on carbon paste electrode," *Biosensors and Bioelectronics*, vol. 22, no. 9–10, pp. 2121–2126, 2007.

[111] R. Nain, H. Patel, M. Chahar, S. Kumar, D. Rohilla, and M. Pal, "Biosynthesized metallic nanoparticles for sustainable environmental remediation: mechanisms, applications, and future perspectives," *Discover Chemistry,* vol. 2, no. 1, p. 124, 2025.

[112] Y. Li, C. Shao, Z. Pei, and Y. Pei, "Recent advancements of nanostructured surface-specific supramolecular assemblies and their application in biomedical engineering," *Green Chemistry*, vol. 27, no. 7, pp. 1871–1894, 2025.

[113] Y. Qin, K. Liu, C. Nie, F. Xie, X. Wang, A. Ali, B. Wang, Q. Hong, and W. Zhao, "One pot preparation of magnetic benzylated cyclodextrin-based hyper-cross-linked polymer for phthalate esters extraction from tea beverages," *Food Chemistry*, vol. 475, no. 1, p. 143253, 2025.

[114] M. Mousavi-Ebadi, and J. Safaei-Ghomi, "Modified magnetic chitosan with mono(6-amino-6-deoxy)-β-cyclodextrin as a novel catalyst toward the synthesis of pyrazolopyrano-pyrimidines and pyrano[2,3-c]pyrazole-3-carboxylates," *Scientific Reports*, vol. 15, no. 1, p. 7863, 2025.

[115] B. Kaboudin, R. Mostafalu, and T. Yokomatsu, "Fe_3O_4 nanoparticle-supported Cu(ii)-β- cyclodextrin complex as a magnetically recoverable and reusable catalyst for the synthesis of symmetrical biaryls and 1,2,3-triazoles from aryl boronic acids," *Green Chemistry*, vol. 15, no. 8, pp. 2266–2274, 2013.

[116] X. Huang, C. Yi, Y. Fan, Y. Zhang, L. Zhao, Z. Liang, and J. Pan, "Magnetic Fe_3O_4 nanoparticles grafted with single-chain antibody (scFv) and docetaxel loaded β-cyclodextrin potential for ovarian cancer dual-targeting therapy," *Materials Science and Engineering: C*, vol. 42, pp. 325–332, 2014.

[117] R. Chalasani, and S. Vasudevan, "Cyclodextrin-functionalized Fe_3O_4@TiO_2: Reusable, magnetic nanoparticles for photocatalytic degradation of endocrine-disrupting chemicals in water supplies," *ACS Nano*, vol. 7, no. 5, pp. 4093–4104, 2013.

[118] Q. M. Kainz, and O. Reiser, "Polymer- and dendrimer-coated magnetic nanoparticles as versatile supports for catalysts,

scavengers, and reagents," *Accounts of Chemical Research*, vol. 47, no. 2, pp. 667–677, 2014.

[119] B. Liu, W. Zhang, F. Yang, H. Feng, and X. Yang, "Facile method for synthesis of Fe_3O_4@polymer microspheres and their application as magnetic support for loading metal nanoparticles," *The Journal of Physical Chemistry C*, vol. 115, no. 32, pp. 15875–15884, 2011.

[120] N. Saifuddin, A. Z. Raziah, and A. R. Junizah, "Carbon nanotubes: A review on structure and their interaction with proteins," *Journal of Chemistry*, vol. 2013, no. 1, p. 676815, 2013.

[121] J. Gallego, J. Tapia, M. Vargas, A. Santamaria, J. Orozco, and D. Lopez, "Synthesis of graphene-coated carbon nanotubes-supported metal nanoparticles as multifunctional hybrid materials," *Carbon,* vol. 111, pp. 393–401, 2017.

[122] S. K. Folsom, D. J. Ivey, F. S. McNair, and A. R. Siamaki, "Nickel-Fe_3O_4 magnetic nanoparticles supported on multiwalled carbon nanotubes: Effective catalyst in suzuki cross coupling reactions," *Catalysts*, vol. 11, no. 4, p. 495, 2021.

[123] E. M. Vunain A. K. Mamba, B. B., "Dendrimers, mesoporous silicas and chitosan-based nanosorbents for the removal of heavy-metal ions: A review," *International Journal of Biological Macromolecules*, vol. 86, pp. 570-586, 2016.

[124] A. Z. Khalifa, O. Cizer, Y. Pontikes, A. Heath, P. Patureau, S. A. Bernal, and A. T. M. Marsh, "Advances in alkali-activation of clay minerals," *Cement and Concrete Research*, vol. 132, p. 106050, 2020.

[125] G. Zhao, J. Wang, Y. Li, X. Chen, and Y. Liu, "Enzymes immobilized on superparamagnetic Fe_3O_4@Clays nanocomposites: Preparation, characterization, and a new strategy for the regeneration of supports," *The Journal of Physical Chemistry C*, vol. 115, no. 14, pp. 6350–6359, 2011.

[126] K. Kalantari, M. B. Ahmad, K. Shameli, M. Z. B. Hussein, R. Khandanlou, and H. Khanehzaei, "Size-controlled synthesis of Fe_3O_4 magnetic nanoparticles in the layers of montmorillonite," *Journal of Nanomaterials*, vol. 2014, pp. 1–10, 2014.

[127] T. R. Flotte, "Gene therapy: The first two decades and the current state-of-the-art," *Journal of Cellular Physiology*, vol. 213, no. 2, pp. 301-305, 2007.

[128] A. Ragusa, I. García, and S. Penadés, "Nanoparticles as nonviral gene delivery vectors," *IEEE transactions on nanobioscience*, vol. 6, no. 4, pp. 319-330, 2007.

[129] D. Cai, J. M. Mataraza, Z.-H Qin, Z. Huang, J. Huang, T. C. Chiles, D. Carnahan, K. Kempa, and Z. Ren, "Highly efficient molecular delivery into mammalian cells using carbon nanotube spearing," *Nature Methods*, vol. 2, no. 6, pp. 449–454, 2005.

[130] S. J. Mattingly, M. G. Otoole, K. T. James, G. J. Clark, and M. H. Nantz, "Magnetic nanoparticle-supported lipid bilayers for drug delivery," *Langmuir*, vol. 31, no. 11, pp. 3326–3332, 2015.

[131] Y. Xu, Y. Shan, Y. Zhang, B. Yu, Y. Shen, and H. Cong, "Multi-functional Fe_3O_4@C-based nanoparticles coupling optical/MRI imaging and pH/photothermal controllable drug release as efficient anti-cancer drug delivery platforms," *Nanotechnology*, vol. 30, no. 42, p. 425102, 2019.

[132] J. Wang, J. Fang, P. Fang, X. Li, S. Wu, W. Zhang, and S. Li, "Preparation of hollow core/shell Fe_3O_4@graphene oxide composites as magnetic targeting drug nanocarriers," *Journal of Biomaterials Science, Polymer Edition*, vol. 28, no. 4, pp. 337–349, 2017.

[133] H. Khurshid, S. H. Kim, M. J. Bonder, L. Colak, B. Ali, S. I. Shah, K. L. Kiick, and G. C. Hadjipanayis, "Development of heparin-coated magnetic nanoparticles for targeted drug delivery applications," *Journal of Applied Physics.*, vol. 105, no. 7, 2009.

[134] N. S. Elbialy, M. M. Fathy, and W. M. Khalil, "Doxorubicin loaded magnetic gold nanoparticles for in vivo targeted drug delivery," *International Journal of Pharmaceutics*, vol. 490, no. 1–2, pp. 190–199, 2015.

[135] S. Liu, B. Yu, S. Wang, Y. Shen, and H. Cong, "Preparation, surface functionalization and application of Fe_3O_4 magnetic nanoparticles," *Advances in Colloid and Interface Science*, vol. 281, p. 102165, 2020.

[136] H. H. S. Hossein, I. Jabbari, A. Zarepour, A. Zarrabi, M. Ashrafizaden, A. Taherian, and P. Makvandi, "Functionalization of magnetic nanoparticles by folate as potential MRI contrast agent for breast cancer diagnostics," *Molecules*, vol. 25, no. 18, p. 4053, 2020.

[137] B. Feng, R. Y. Hong, L. S. Wang, L. Guo, H. Z. Li, J. Ding, Y. Zheng, and D. G. Wei, "Synthesis of Fe_3O_4/APTES/PEG diacid functionalized magnetic nanoparticles for MR imaging," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 328, no. 1–3, pp. 52–59, 2008.

[138] A. S. Davydov, A. V. Belousov, G. A. Krusanov, M. A. Kolyvanova, B. B. Kovalev, A. S. Komlev, P. V. Krivoshapkin, V. N. Morozov, and V. I. Zverev, "Promising magnetic nanoradiosensitizers for combination of tumor hyperthermia and x-ray therapy: Theoretical calculation," *Journal of Applied Physics,* vol. 129, no. 3, p. 033902, 2021.

[139] P. H. Nam, L. T. Lu, P. H. Linh, D. H. Manh, L. T. T. Tam, N. X. Phuc, P. T. Phong, and I-J. Lee, "Polymer-coated cobalt ferrite nanoparticles: Synthesis, characterization, and toxicity for hyperthermia applications," *New Journal of Chemistry*, vol. 42, no. 17, pp. 14530–14541, 2018.

[140] I. Crăciunescu, P. Palade, N. Iacob, G. M. Ispas, A. E. Stanciu, V. Kuncser, and R. P. Turcu, "High-performance functionalized magnetic nanoparticles with tailored sizes and shapes for localized hyperthermia applications," *The Journal of Physical Chemistry C*, vol. 125, no. 20, pp. 11132–11146, 2021.

[141] O. K. Arriortua, M. Insausti, L. Lezama, I, G. de, Muro, E. Garaio, J. M. de la Fuente, R. M. Fratila, M. P. Morales, R. Costa, M. Eceiza, M. Sagartzazu-Aizpurua, and J. M. Aizpurua, "RGD-Functionalized Fe_3O_4 nanoparticles for magnetic hyperthermia," *Colloids Surfaces B Biointerfaces*, vol. 165, pp. 315–324, 2018.

[142] W. Zhang, L. Y. Zhang, X. J. Zhao, and Z. Zhou, "Citrus pectin derived ultrasmall Fe_3O_4@C nanoparticles as a high-performance adsorbent toward removal of methylene blue," *Journal of Molecular Liquids*, vol. 222, pp. 995–1002, 2016.

[143] R. H. Hesas, M. S. Baei, H. Rostami, J. Gardy, and A. Hassanpour, "An investigation on the capability of magnetically separable Fe_3O_4/mordenite zeolite for refinery oily wastewater purification," *Journal of Environmental Management,* vol. 241, pp. 525–534, 2019.

[144] N. C. Feitoza, T. D. Goncalves, J. J. Mesquita, J. S. Menegucci, M-K. M. S. Santos, J. A. Chaker, R. B. Cunha, A. M. M. Medeiros, J. C. Rubim, and M. H. Sousa, "Fabrication of glycine-functionalized maghemite nanoparticles for magnetic removal of copper from wastewater," *Journal of Hazardous Materials.*, vol. 264, pp. 153–160, 2014.

[145] A. A. Babaei, B. Kakavandi, M. Rafiee, F. Kalantarhormizi, I. Purkaram, E. Ahmadi, and S. Esmaeili, "Comparative treatment of textile wastewater by adsorption, Fenton, UV-Fenton and US-Fenton using magnetic nanoparticles-functionalized carbon (MNPs@C)," *Journal of Industrial and Engineering Chemistry*, vol. 56, pp. 163–174, 2017.

[146] X. Liu, J. Tian, Y. Li, N. Sun, S. Mi, Y. Xie, and Z. Chen, "Enhanced dyes adsorption from wastewater *via* Fe_3O_4 nanoparticles functionalized activated carbon," *Journal of Hazardous Materials.*, vol. 373, pp. 397–407, 2019.

[147] Q. Zhang, Q. Xu, Y. Guo, X. Sun, and X. Wang, "Acetylcholinesterase biosensor based on the mesoporous carbon/ferroferric oxide modified electrode for detecting organophosphorus pesticides," *RSC Advances*, vol. 6, no. 29, pp. 24698–24703, 2016.

[148] M. Eguílaz, R. Villalonga, P. Yáñez-Sedeño, and J. M. Pingarrón, "Designing electrochemical interfaces with functionalized magnetic nanoparticles and wrapped carbon nanotubes as platforms for the construction of high-performance bienzyme biosensors," *Analytical Chemistry*, vol. 83, no. 20, pp. 7807–7814, 2011.

[149] W. Zhang, C. Chen, D. Yang, G. Dong, S. Jia, B. Zhao, L. Yan, Q. Yao, A. Sunna, and Y. Liu "Optical biosensors based on nitrogen-doped graphene functionalized with magnetic nanoparticles," *Advanced Materials Interfaces*, vol. 3, no. 20, p. 1600590, 2016.

[150] R. J. White, R. Luque, V. L. Budarin, J. H. Clark, and D. J. Macquarrie, "Supported metal nanoparticles on porous materials. methods and applications," *Chemical Society Reviews*, vol. 38, no. 2, pp. 481–494, 2009.

[151] F. Zhang, J. Jin, X. Zhong, S. Li, J. Niu, R. Li, and J. Ma, "Pd immobilized on amine-functionalized magnetite nanoparticles: A novel and Highly active catalyst for hydrogenation and Heck reactions," *Green Chemistry*, vol. 13, no. 5, pp. 1238–1243, 2011.

[152] G. J. Hutchings, "Nanocrystalline gold and gold palladium alloy catalysts for chemical synthesis," *Chemical Communications*, no. 10, pp. 1148-1164, 2008.

[153] M. Hajjami, and S. Kolivand, "New metal complexes supported on Fe_3O_4 magnetic nanoparticles as recoverable catalysts for selective oxidation of sulfides to sulfoxides," *Applied Organometallic Chemistry*, vol. 30, no. 5, pp. 282–288, 2016.

[154] F. Rajabi, S. Naserian, A. Primo, and R. Luque, "Efficient and highly selective aqueous oxidation of sulfides to sulfoxides at room temperature catalysed by supported iron oxide nanoparticles on SBA-15," *Advanced Synthesis & Catalysis*, vol. 353, no. 11–12, pp. 2060–2066, 2011.

[155] M. Khodakarami, and M. Bagheri, "Recent advances in synthesis and application of polymer nanocomposites for water and wastewater treatment," *Journal of Cleaner Production*, vol. 296, p. 126404, 2021.

[156] S. K. Sharma, N. Shrivastava, F. Rossi, L. D. Tung, and N. T. K, Thanh, "Nanoparticles-based magnetic and photo induced hyperthermia for cancer treatment," *Nano Today*, vol. 29, p. 100795, 2019.

[157] G. Rando, S. Sfameni, M. Galletta, D. Drommi, S. Cappello, and M. R. Plutino, "Functional nanohybrids and nanocomposites development for the removal of environmental pollutants and bioremediation," *Molecules*, vol. 27, no. 15, p. 4856, 2022.

[158] A. M. Abu-Dief, and S. M. Abdel-Fatah, "Development and functionalization of magnetic nanoparticles as powerful and green catalysts for organic synthesis," *Beni-Suef University Journal of Basic and Applied Sciences*, vol. 7, no. 1, pp. 55–67, 2018.

[159] X. Duan, J. Liu, J. Hao, L. Wu, B. He, Y. Qiu, J. Zhang, Z. He, J. Xi, and S. Wang, "Magnetically recyclable nanocatalyst with synergetic catalytic effect and its application for 4-nitrophenol reduction and Suzuki coupling reactions," *Carbon,* vol. 130, pp. 806–813, 2018.