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Magnetite Nanomaterials: Synthesis, Characterization, and Multifaceted Applications

Noor Zulfiqar[1,*], **Ihtisham Ahmad**[2], **Kinza Ali**[3], **Muhammad Arsalan**[4], **Satyadhar Joshi**[5]

[1]Department of Chemistry, Faculty of Science, University of Agriculture, Faisalabad, Punjab 38000, Pakistan.
[2]Department of Sustainable Environment and Energy Systems, Middle East Technical University, Northern Cyprus Campus, Kalkanli 99738, Guzelyurt, Mersin, Turkey.
[3]Faculty of Industrial Sciences and Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Kuantan 26300, Malaysia.
[4]University of the Chinese Academy of Sciences, Beijing 100039, China.
[5]Department Information Technology, MSIT Alumnus, Touro College, New York, NY 10010, USA.

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[*]**Corresponding author:** Noor Zulfiqar, Department of Chemistry, Faculty of Science, University of Agriculture, Faisalabad, Punjab 38000, Pakistan.

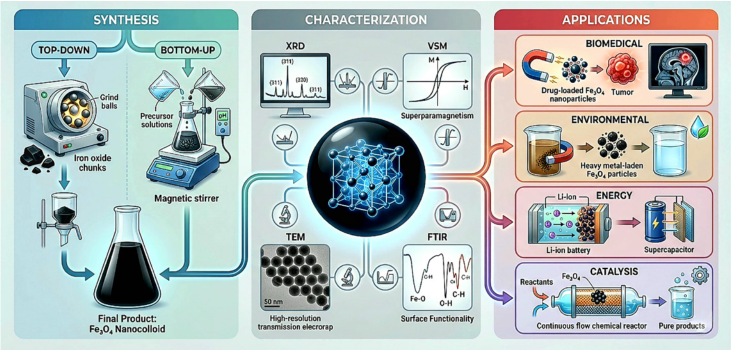
Abstract

Nanomaterials, defined as materials with at least one dimension below 100 nm, have gained immense attention due to their unique physicochemical, electrical, optical, and magnetic properties that differ significantly from bulk materials. Among them, magnetite nanoparticles (Fe_3O_4) and their nanocomposites stand out for their tunable surface chemistry, biocompatibility, and ease of magnetic recovery, enabling wide-ranging applications in medicine, catalysis, environmental remediation, electronics, and biotechnology. This study provides a comprehensive overview of magnetite nanoparticles and nanocomposites, including their synthesis strategies with emphasis on green and sustainable approaches, structural characteristics, and functional performance. Characterization techniques such as UV–Vis spectroscopy, FTIR, SEM, and EDX are discussed to highlight methods for evaluating their morphology, crystallinity, and composition. Particular attention is given to their role in targeted drug delivery, bioimaging, antimicrobial activity, heavy metal adsorption, and wastewater treatment, demonstrating their versatility in addressing environmental and biomedical challenges. By summarizing recent advances, challenges, and opportunities, this review offers a consolidated understanding of magnetite nanomaterials as a platform for next-generation technologies.

Keywords

Magnetite nanoparticles; Magnetite nanocomposites; Green synthesis; Biochar; Nanomaterials; Environmental remediation; Drug delivery; Antimicrobial activity; Heavy metal adsorption; Characterization techniques

Graphical Abstract



1. Introduction

Nanomaterials are a wide range of materials that involve particular nano substances (nanoparticles), having one dimension less than a hundred nanometers at least. It originates from the Greek word nano, which stands for "dwarf". It is a new advancement in science, with numerous practical applications in medicine. Nanostructured constituents give a larger surface area that improves the rate of reaction, which has been used in a few fields, for example, medication, environment, food, biotechnology, drug delivery, fabrics, agribusiness, and vitality. Nanomaterials have exceptional electrical, optical, and magnetic properties compared to the bulk materials that brought the technological revolution. These properties vary according to their size, shape, and structure of the nanoparticles, which can be further refined by optimization of the synthetic method [1-3].

Magnetite nanoparticles are very fascinating because of their numerous properties, for example effect of size, magnetic isolation, specificness, as well as surface chemistry. Magnetite nanocomposite has a structure like a core-shell. Magnetite as well as iron oxyhydroxide nanocomposite are synthesized when the metallic core shell in iron nanoparticles is oxidized. The functional mechanism of magnetite (Fe_3O_4) Nanocomposite relies on several mechanisms that occur among the layers of core-shell, for example, diffusion & casualization at the core part for strong oxidizing agents [4-6].

Table 1. Overview of Magnetite (Fe_3O_4) Nanoparticles and Nanocomposites – Synthesis, Properties, Characterization, and Applications

Aspect	Details/Examples	Key Features/Advantages
Material Type	Magnetite nanoparticles (Fe_3O_4), Magnetite-based nanocomposites (e.g., Fe_3O_4/biochar, Fe_3O_4/graphene, Fe_3O_4/phenol-formaldehyde resin)	Superparamagnetic, biocompatible, high surface area, core-shell structures
Particle Size	Typically 10-50 nm (depending on synthesis)	Small size enhances surface reactivity, adsorption capacity, and biomedical uptake
Synthesis Methods	- Green synthesis (plant extracts, e.g., Eucalyptus globulus) - Chemical co-precipitation - Hydrothermal synthesis - Thermal decomposition	Eco-friendly, tunable particle size, scalable, cost-effective
Surface Functionalization	Coating with biochar, silica, polymers, or organic ligands	Stabilizes nanoparticles, prevents aggregation, improves selectivity, biocompatibility
Magnetic Properties	Superparamagnetism, magnetic saturation up to 69.2 emu/g	Allows easy magnetic separation, recovery, and targeted drug delivery
Characterization Techniques	UV-Vis spectroscopy, FTIR, SEM, TEM, XRD, EDX	Determines particle size, morphology, crystallinity, elemental composition, surface groups
Biomedical Applications	Drug delivery, hyperthermia treatment, MRI contrast agents	Targeted therapy, reduced side effects, imaging enhancement
Antimicrobial Applications	Gram-positive and Gram-negative bacteria	Strong antibacterial activity due to high surface area and reactivity
Environmental Applications	Adsorption of heavy metals, degradation of antibiotics and dyes, water treatment	High adsorption capacity, photocatalysis, reusability via magnetic separation
Catalytic Applications	Fenton-like reactions, organic pollutant degradation	Enhanced reaction rates due to high surface area and active sites
Advantages of Magnetite Nanocomposites	- Increased surface area and porosity - Thermal and mechanical stability - Synergistic functional properties	Better performance than individual nanoparticles, multifunctional use
Limitations	Agglomeration, limited large-scale synthesis, potential environmental and biological toxicity	May affect reusability, reproducibility, and industrial translation
Future Directions	Green synthesis, hybrid composites (graphene, MOFs, biochar), AI-guided design, toxicity assessment	Improved stability, scalability, multifunctionality, and safety

A composite is synthesized by combining at least two different constituents. These are blended to get the improved characteristics of both materials. A composite is a mixture of two constituents with distinctive properties to give a material with characteristics better than both the constituents taken separately [7]. A nanocomposite is formed when nanoparticles are loaded on a solid reinforcement that increases surface area and gives stability. Nanocomposites contain nanoscale pores that exhibit higher selectivity, permeability, good thermal stability, and mechanical stability [1, 8, 9]. Constituents of a nanocomposite have a high surface-to-volume ratio due to their small size and surface activity. That is the reason nano-constituents act as support in increasing mechanical properties for packaging material of food; furthermore, it provides the unique structures for smart and active wrapping applications. Bio-composites are an explicit type of constituents which have a fine stage measurement, especially a few nanometers [10, 11]. Magnetite nanocomposites generally retain high adaptability, for example, they show unobtrusive development, small particle size, large surface area to volume ratio, bio-adsorption and photo catalytic advantages. As compare to others, magnetite nanocomposite is beneficial, viable, and have better outcomes towards wastewater treatment because they can remove micro-contaminants of various ranges and different types of environmental waste from agro waste. Iron oxide nanocomposites are classified into different categories, such as antiferromagnetic hematite (Fe_2O_3), supermagnetic magnetite (Fe_3O_4), and orthorhombic composite structures [5, 12].

Magnetite nanocomposites have been used extensively owing to their extraordinary properties, such as good catalytic properties, greater chemical reactivity, magnetite properties, large surface area, smaller size, and microwave absorption properties. The above-mentioned characteristics have enhanced the use of iron oxide nanocomposites in different fields like bio-imaging, diagnosis, gene delivery, drug delivery, catalysis, cell separation, and tumor therapy. Iron oxide nanocomposites have scope in physics, chemistry, industry, medicine, material sciences, also used in hard drives for data storage, bioremediation of the environment, in MRI scanners for detailed imaging of body organs, and degradation of antibiotics from wastewater [13-15].

Magnetite Nanocomposites are colloidal iron oxide (Fe_3O_4) materials that display superparamagnetic characteristics at room temperatures. Magnetite nanocomposites are used in nanotoxicology and magnetic nanotechnology fields of research and advancement. Their size, non-toxic nature, and superparamagnetic characteristics make them fascinating for applications in numerous fields, e.g., biosensors, catalysis, magnetic separations, ferro fluids, as well as in magnetic resonance imaging. Magnetite nanoparticles from the nano composite are roughly 20 nm in size. This magnetite material is unwounded, profoundly concentrated, and introduced in the aqueous solution as a dried powder that promptly redisperses in the water [16].

Magnetite nanocomposites were efficiently manufactured by chemical co-precipitation of precursors of magnetite in the plant leaves extract. It was noted that the characteristics of the nanocomposites were an imprint of the properties of magnetite nanostructures. Increasing the ratio of magnetite in the nanocomposites increases the magnetic properties, higher surface area, thermal stability aa well as better crystallinity. Decreasing the amount of magnetite, or increasing the amount of carbon content in the nanocomposites, leads to a smaller particle size, and the rate of agglomeration was also decreased [17, 18].

1.1 Magnetite nanosized particles

Magnetite nanoparticles have outstanding properties, such as being synthesized cheaply and easily, having a small size, high magnetism, being biocompatible, having microwave absorption properties, surface chemical properties, catalytic properties, better stability, and being recoverable easily by using an external magnet. These properties widen the applications of magnetite nanoparticles, i.e., medical implications containing identification, drug delivery, DNA repairing, cyst therapy, cell parting, disciplines including physics, chemistry, industry, medicine, material sciences, hard drives for storage of data, degradation of dyes, environmental bioremediation, expulsion of natural and inorganic toxins from water. Nanoscience has interlinked different trains and broadened the scope of use, for example, prescription, treatment, chemical sensors, biosensors, and environmental applications [5]. Magnetite nanoparticles are interesting owing to their properties, i.e., high coactivity, super para magnetism, interparticle interactions, and intraparticle interactions. Magnetite nanoparticles can be separated from the solution using a permanent magnet for further use. Attributable to their size in nanometers, such particles end up being of significance in organic applications [19]. For bio related application, biocompatibility is a significant factor.

For such reason, iron oxide nanomaterials are approved by the FDA (Food and Drug Administration) and EMA (European Medicines Agency). Magnetite Fe3O4, magnetite Fe2O3, and other iron oxides are the most studied. As of late Nano particles are being utilized as adsorbents because of their enormous surface area and synthetic reactivity.

Thus, for the disconnection of substantial metals from waste waters Nano adsorbents are utilized, including graphene, CNT's, and metallic oxides, and so on. Oxide based Nano particles are, for the most part, inorganic in nature.

TiO2, ZnO, MgO, and Fe2O3 are a portion of the models. Nano-adsorbents for substantial metal evacuation ought to be less lethal, adsorb heavy metals at parts per billion scale, and be reusable. Size, agglomeration state, shape, chemical composition, crystalline structures, and solubility are a portion of the fundamental components controlling nano-adsorbent properties. Out of magnetite nanoparticles, magnetite is considered most efficient [20].

1.2 Magnetite nanocomposite materials

A composite material is made up of two materials that have distinct physical and chemical properties. When they are combined, they form a material that is advanced to perform a specific task, such as becoming stronger, lighter, or more resistant to electricity. They can also cope with stiffness and strength. The materials are mixed to form a composite material. Constituent materials are individual materials that make up a product, and there are two types of them. The matrix (binder) is one, and the reinforcement is the other. Therefore, at least some of each type is required. When the matrix surrounds the reinforcement and maintains its relative position, the reinforcement is supported by the matrix. As the reinforcements add their exceptional physicochemical characteristics, the matrix properties are bolstered. Synergism makes the mechanical properties of the individual constituent materials obsolete. At the same time, the product or structure's designer has the choice of selecting the best combination of matrix and reinforcing materials from a vast selection [21].

A nanocomposite is a composite material in which one of the elements has at least one dimension, which is about 10-9m in size, nanoscopic. These nanocomposites have enhanced properties when contrasted with the individual component materials through the synergetic influence of both components. Nanocomposites possess multifunctional properties like a high surface to volume ratio for loading of biomolecules such as enzymes, high mechanical strength (increased stability with no decrease of strength- scratching resistance), catalytic activity due to nano size, high electric conductivity, thermal stability, chemical resistance, low weight, and cost-effective [5, 22].

Recently, development in the field of nanocomposites has opened new technological prospects for application in a rapidly developing field. With increasing nanocomposites efficiency, these materials are useful in many fields, from packaging to biomedical applications. Biochar-based nanocomposites may be synthesized not only to enhance the physical and chemical properties of biochar but also to produce modern composites to integrate the benefits of biochar with nanomaterials. The resulting composites usually show great improvement in functional group, porous properties, active sites of the surface, catalytic degradation, and fast separation.

Such composites have the potential to adsorb pollutants from aqueous solutions, and they may be used as a potential sorbent for contaminated soil and sediment management [23, 24]. Biochar coated with catalytic material will simultaneously exert adsorption and catalytic degradation features for the removal of organic pollutants from wastewater. A nanocomposite is a multiphase solid material where one of the phases has one, two, or three dimensions of less than 100 nanometers (nm) or structures having nano-scale repeat distances between the different phases that make up the material. The idea behind Nanocomposites is to use building blocks with dimensions in nano meter range to design and create new materials with unprecedented flexibility and improvement in their physical properties. In the broadest sense, this definition can include porous media, colloids, gels, and copolymers, but is more usually taken to mean the solid combination of a bulk matrix and nano-dimensional phase(s) differing in properties due to dissimilarities in structure and chemistry. The mechanical, electrical, thermal, optical, electrochemical, and catalytic properties of the nanocomposite will differ markedly from those of the component materials. Nanocomposites are found in nature, for example, in the structure of the abalone shell and bone. The use of nanoparticle-rich materials long predates the understanding of the physical and chemical nature of these materials [25-27].

Recently, many researchers have focused on magnetite nanomaterials because of their outstanding characteristics and easy isolation methods in adsorption and other techniques. Using iron-based nanomaterials allowed the separation process to be not only simple through the use of a magnetic field but also boosted the overall performance by enhancing the adsorption capacity. Recently, nanocomposite Fe_2O_3/biochar derived from the pyrolysis of agro waste has shown excellent efficiency for removing aqueous heavy metals. Furthermore, the highest value of magnetic saturation,69.2 emu/g, allowed for easier magnetic isolation from an aqueous solution. The higher surface area of nanomaterials has definite importance in terms of ion uptake in the adsorption process. Research has reported the production of a nanocomposite. Fe_3O_4/phenol-formaldehyde resin that was synthesized by hydrothermal carbonization. The highly ultra-fine size of 3.2 nm of carbon aerogel, which showed a higher surface area of 487 m^2/g, was formed. In addition, it was used for removing arsenic from water, exhibiting a higher adsorption capacity of 216.9 mg/g. The nano size of Fe_3O_4-based adsorbents was found suitable for the transmission of arsenic ions from an aqueous solution to the electrostatic site on the surface of the nanocomposite.

Moreover, by using an iron oxide–based nanocomposite, the surface of the material was stabilized with the help of organic or inorganic modification, which also protects the material from oxidation and therefore offers a special upgrade in the material that can be helpful in improving overall performance in the adsorption of heavy metals.

2. Synthesis of Magnetite Nanomaterials

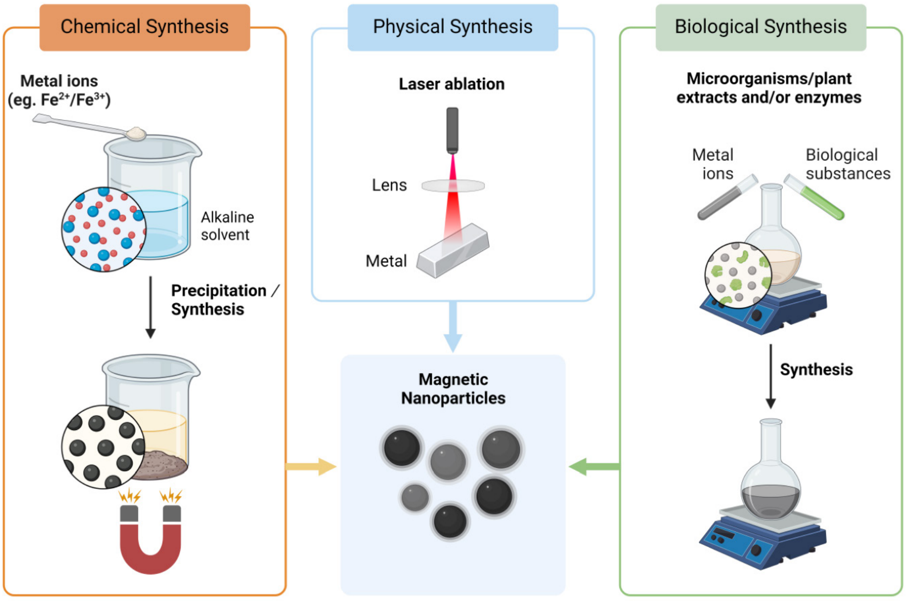


Figure 1. Phyto-fabrication of magnetite NPs [30].

Magnetite nanoparticles (Fe_3O_4 NPs) have attracted considerable attention due to their unique magnetic properties and diverse applications in biomedicine, environmental remediation, and catalysis. Among various synthetic approaches, green synthesis has emerged as an environmentally friendly and sustainable method, avoiding the use of toxic chemicals. For instance, leaf extracts of *Eucalyptus globulus* can serve simultaneously as reducing, stabilizing, and capping agents in the fabrication of magnetite nanoparticles. In this process, an iron precursor such as ferric chloride hexahydrate ($FeCl_3 \cdot 6H_2O$) is mixed with the plant extract under continuous stirring at elevated temperatures (~80°C). Sodium hydroxide is added dropwise until the formation of a dark black precipitate, which is then subjected to drying at 400-500°C to yield black powdered magnetite nanoparticles. In addition to green synthesis, magnetite nanoparticles can also be prepared by co-precipitation, thermal decomposition, solvothermal/hydrothermal, and microemulsion techniques, each offering control over particle size, morphology, and magnetic properties. While chemical and physical methods, as shown in Figure 1, often provide precise size tuning and crystallinity, green synthesis offers biocompatibility and eco-friendliness, making it highly suitable for biomedical applications such as drug delivery, magnetic resonance imaging (MRI), and cancer cell targeting [28, 29].

For the preparation of magnetite/biochar nanocomposites, biochar is first processed to the nanoscale by sieving through a nano sieve, ensuring uniform particle size. A weight ratio of 1:2 is maintained between magnetite nanoparticles and nano-biochar powder. In a typical procedure, 2 g of magnetite nanoparticles and 4 g of sieved biochar are dispersed in distilled water, which acts as a medium, and the mixture is agitated on a shaker at 313 rpm for 4 hours at 25°C to promote uniform interaction and composite formation. The resulting magnetite/biochar nanocomposite is then separated from the aqueous medium using an external magnet, washed to remove unbound particles, and subsequently dried in an oven. The dry nanocomposite is collected and stored in airtight containers for further applications, such as adsorption, catalysis, or environmental remediation. This straightforward synthesis approach ensures efficient integration of magnetite nanoparticles with biochar, enhancing the composite's magnetic and surface-active properties while maintaining eco-friendly and cost-effective processing conditions.

3. Characterization Techniques for Nanomaterials

Magnetite nanocomposite and magnetite nanoparticles are mainly characterized by their: i) shape, ii) size, iii) pore volume and distribution, and iv) surface area. Selectivity, toxicity, lifetime, ease of preparation, and cost are parameters to consider when choosing the ideal catalyst. Different techniques, such as UV-Visible spectrophotometer, scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), among others, were used to physically characterize the produced photocatalysts. The different characterization techniques are given below:

3.1 Ultraviolet-visible spectroscopy

A UV-Visible spectrophotometer is used to study the absorption behavior of a substance in the ultraviolet region, ranging from 10 to 800 nm [31].

3.1.1 Advantages of UV-Visible spectrophotometer

✓ Ability to examine substances quickly
✓ Usage of the UV-Visible spectrophotometer is easy
✓ A minute amount of sample is needed
✓ Quantitative analysis of different chemical species, for example, transition metallic ions, conjugate organic analytes, as well as organic macromolecules.

3.1.2 Components of a UV-Visible spectrophotometer

✓ light source
✓ Monochromator
✓ Sample holder
✓ Detector
✓ Interpreter

3.1.3 Principle of UV/VIS Spectroscopy

The absorption of UV/Vis rays by molecules is related to the excitation of valence e^- from the ground state to the higher energy states. Electronic transitions usually occur from the highest occupied molecular orbital (bonding or nonbonding) to the lowest unoccupied molecular orbital (antibonding). The wavelength of the rays that are absorbed depends on the difference in energy between the orbital primarily occupied by the e^- and the orbital to which it is jumping. When a molecule absorbs UV/Vis rays of a discrete wavelength, only one photon is absorbed, and it is supposed that only one electron is excited to a higher energy level while leaving another electron remaining electro. A schematic diagram of a UV-Visible Spectrophotometer is given in Fig 2.

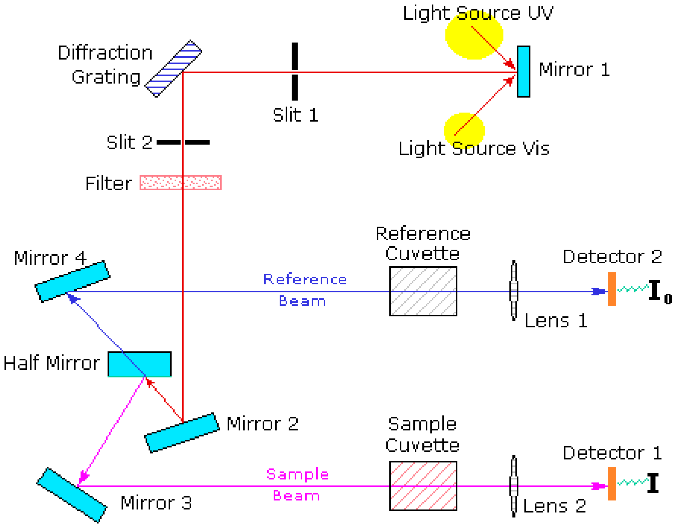


Figure 2. Schematic diagram of UV-Visible Spectrophotometer.

3.2 Fourier transform-infrared spectroscopy

The interaction between capping agents and NPs is demonstrated by this technique. The interactions of functional groups of biomolecules and metal NPs are observed. IR spectra shows a number of absorption bands which are also distinguished with very minute differences. The unique features have been observed for NPs owing to their high surface area. The vibrational spectrum of NPs is examined by the atoms present at surface. In this technique, light is emitted from a source, a beam splitter divides it into two halves; 1st half enters the sample, while 2nd half goes to the control. The NPs adsorb light according to their properties [32]. A detector sent an electrical signal to an analog recorder. A schematic diagram of the FT-IR Spectrophotometer is given in Fig. 3.

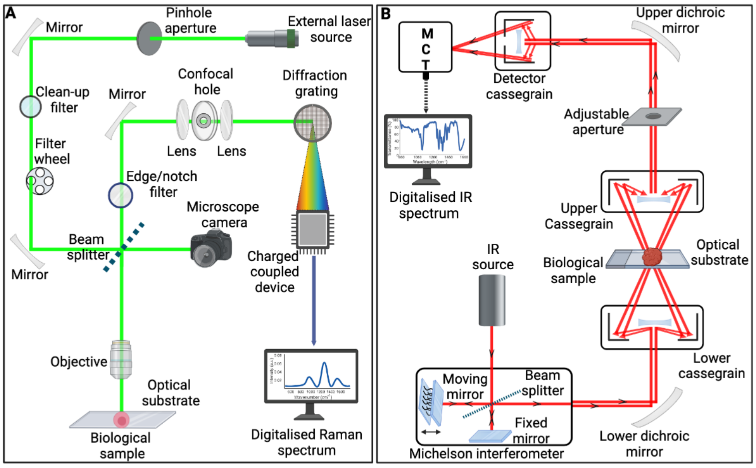


Figure 3. Schematic diagram of FT-IR Spectrophotometer [32].

3.3 Scanning electron microscopy (SEM) analysis

SEM is a type of electron microscope by which images of a sample are produced by scanning the surface of the target substance with a beam of electrons. Signals are generated by the interaction of electrons with the atoms of the sample that give information about composition and surface topography. Secondary electrons are released from atoms by exciting the sample, that detected electron intensity from most of the common SEM modes. It depends on the specimen. SEM analysis can show better resolving power than 1nm. A Hitachi ultra-high-resolution field emission scanning electron microscopy is used to investigate the surface topography of the nanocomposite. The cold field emission gun, with a small energy spread emitted electrons interacts with the atoms in the sample surface. Many signals were then derived from such an electron-sample interaction. Received by the detector, these signals containing sample information (e.g., external morphology, crystalline structure, chemical information, and orientation of materials) were consequently converted to ultra-high-resolution images. Fig 4 shows the diagram of the Scanning Electron Microscope (SEM) [19, 33].

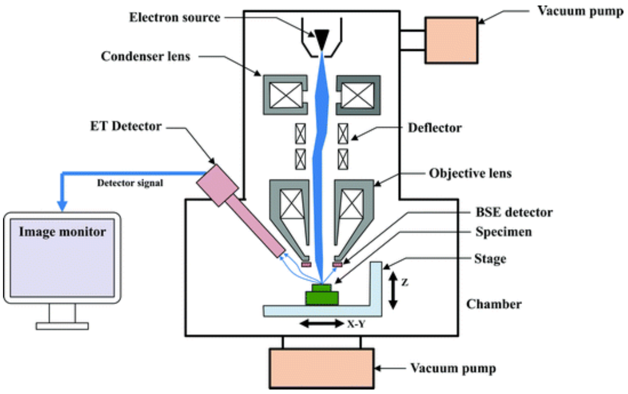


Figure 4. Schematic diagram of Scanning Electron Microscope (SEM) [34].

3.4 Energy dispersive X-ray (EDX) analysis

Energy dispersive X-ray analysis (EDX) is an analytical technique used for elemental analysis. The data obtained in the form of spectra that show peaks about elements' composition of the target sample. When a sample is bombarded by an electron beam, inner shell electrons are ejected; after this electron from higher energy levels go to the inner shells, producing higher energy photons in the X-ray range. The silver and other elementary compositions are confirmed by this technique. TEM was employed to perform EDX analysis of samples. The EDX technique is non-destructive, and specimens of interest can be examined in situ with little or no sample preparation. EDX Analysis also determines stoichiometry, elemental composition, and chemical purity of prepared magnetite nanoparticles and magnetite NC's. Fig. 5 shows a diagram for the Principle of EDX [35].

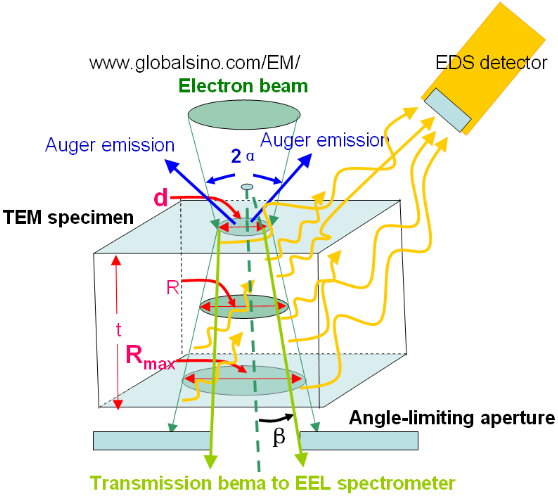


Figure 5. Schematic diagram for the Principle of EDX [36].

4. Applications of Magnetite Nanomaterials

4.1 Medicinal applications

Use of magnetite nano or micro particles as drug carriers to targeted tumor cells was first proposed in the 1970s. The therapeutic drug can be either attached to or encapsulated within magnetite nanoparticles. These drug carriers are injected into the bloodstream close to the cancer site. Magnetic fields are used to move these magnetite nanoparticles. While this is effective for sites on the body's surface, it easily becomes difficult to target internal organs. Hyperthermia is an alternative approach to cancer treatment that involves heating the cancerous cells without damaging the nearby cells. Injecting magnetite nanoparticles near the tumor and heating them up by alternating magnetic fields achieves this. Alternating the direction of the magnetic fields results in changing particle magnetization, which in turn results in hysteresis or heating up of the particles.

4.1.1 Administration of medicine

Magnetite NPs are used extensively for drug delivery due to their high stability. The use of magnetite nanoparticles is an effective and safe means to administer drugs and eliminates the side effects of standard chemotherapy. The smaller scale and greater area of NP drug transporters will shield them from degradation and increase precipitation time. However, magnetite nanoparticles face many obstacles when providing drugs to targeted tissues in the body, such as the need to penetrate the vascular endothelium biological barrier [37]. The performance of magnetite nanoparticles, however, depends on the distance, the chemical morphology of the surface, and the charge. Big NPs greater than 200 nm can be stopped by splenic macrophages, whereas tiny NPs smaller than 10 nm can be quickly removed by extravasation and renal clearance. Around the same time, particles that are 10-100 nm in diameter are the safest form of injection. To facilitate drug delivery and identification, the new embedded and coated NP core has been optimized. Moreover, certain hazardous NPs with high magnetic moments can be used in the use of modern surface coatings (such as gold or silica shells). Moreover, hollow microspheres, such as silicon dioxide-coated magnetite, can carry a significant range of drugs and can be controlled by an externally applied magnetic field.

4.2 Identification

Magnetite nanoparticles are widely utilized as contrast agents in magnetic resonance imaging (MRI) because of their superparamagnetic properties, which enhance image contrast and improve the sensitivity of MRI scans. Their ability to alter the relaxation times (T1 and T2) of surrounding hydrogen protons makes them particularly effective for high-resolution imaging. By functionalizing their surfaces with targeting ligands, antibodies, or peptides, these nanoparticles can selectively bind to cancerous cells, enabling the precise differentiation of malignant tissues from healthy ones. This targeted imaging capability not only improves early cancer detection but also supports image-guided therapy and monitoring of treatment efficacy.

4.3 Antimicrobial applications

The magnetite nanoparticle showed a strong antimicrobial effect. Their antimicrobial action might be related to the small size of iron oxide NPs. Their antimicrobial activity impact was better for Gram-positive bacteria compared to Gram-negative. These nanoparticles proved antimicrobial activity for various types of bacteria [38, 39].

4.4 Separating agents

Magnetite particles and fluids have also been used for separating cells and proteins. In biological applications, the particles have a ligand to which a specific protein or cell can attach and be separated from the solution by magnetic means.

4.5 Environmental role

Some of the other applications involve using nano magnetite particles as a selective photocatalyst material for targeted solutes, such as radionuclides, antibiotics, heavy metals, pesticides, or organic dyes [40]. Highly porous magnetic beads have also been used effectively for removing metal ions from water. It has also been demonstrated that nanoscale bimetallic particles are effective in the transformation of trichloroethene (TCE) into benign hydrocarbons like ethane. NPs of bimetals of Fe-Ni show an acceleration of the reduction of chloroform. Recently, iron NPs have been used for arsenic removal from drinking water. In addition, field implementations of nanomaterials for environmental cleanup have also been gaining popularity [41]. This thesis addresses the practicability of using functionalized magnetite nanostructures for the removal of antibiotics from an aqueous stream [8].

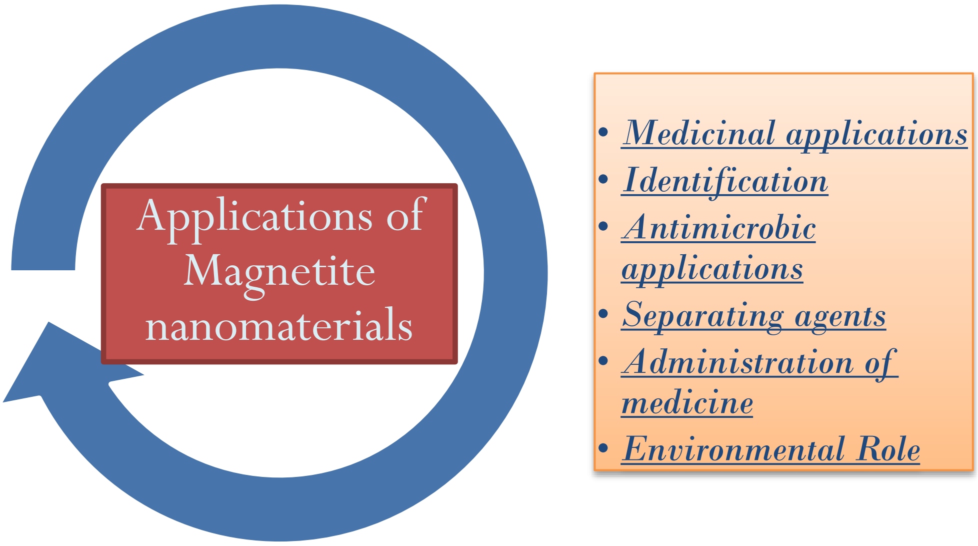


Figure 6. Applications of Magnetite nanoparticles.

5. Limitations and Future Perspectives

5.1 Limitations

Despite their remarkable versatility, magnetite nanoparticles and nanocomposites face several challenges that hinder their widespread adoption in biomedical, environmental, and industrial sectors:

(1) Agglomeration and Stability Issues
Due to their high surface energy and magnetic properties, magnetite nanoparticles tend to agglomerate, reducing surface area and functional performance. This limits their reusability and consistency in catalytic or adsorption processes.

(2) Synthesis Challenges
Many synthesis methods, particularly chemical and thermal routes, require expensive precursors, high energy inputs, and multiple purification steps, which make large-scale production costly. Even green synthesis methods lack scalability and often result in heterogeneous particle sizes.

(3) Surface Functionalization Complexity
Achieving precise surface modification is critical for biomedical applications, yet the process remains time-intensive and may involve toxic solvents or reagents, which contradict the goal of sustainable nanomaterials.

(4) Environmental and Biological Toxicity
Limited research has been conducted on the long-term ecotoxicological impact of magnetite nanomaterials. Concerns include bioaccumulation, oxidative stress in biological systems, and potential groundwater contamination during large-scale environmental remediation efforts.

（5) Lack of Standardization
There is no universal protocol for nanoparticle characterization, leading to inconsistencies in size, shape, crystallinity, and magnetic property measurements across different studies. This limits reproducibility and industrial translation.

(6) Economic Constraints
The high cost of advanced characterization tools (SEM, TEM, XPS) and specialized coatings increases production costs, creating a gap between laboratory-scale innovation and industrial application.

5.2 Future Perspectives

(1) Green and Scalable Synthesis
Future research should emphasize eco-friendly, energy-efficient, and cost-effective synthesis methods, such as plant-based extracts, microbial synthesis, or waste-derived precursors, to make magnetite nanomaterials industrially viable.

(2) Surface Engineering and Functionalization
Advanced functionalization techniques, including biomolecule conjugation, polymer coatings, and hybrid nanostructures, can enhance biocompatibility, stability, and selectivity for biomedical and environmental targets.

(3) Toxicological and Regulatory Studies
Comprehensive in vitro and in vivo toxicity assessments are essential to establish safe concentration ranges, degradation pathways, and environmental impacts of magnetite nanoparticles, paving the way for clinical and environmental approvals.

(4) Hybrid and Smart Nanocomposites
Integration with advanced materials like graphene, carbon nanotubes, MOFs, or biochar can create multifunctional composites with enhanced magnetic, catalytic, and adsorption properties for targeted applications [42].

(5) Industrial Scale-Up and Commercialization
Research should focus on developing cost-effective synthesis routes, batch-to-batch consistency, and reusable nanocomposites, enabling transition from laboratory prototypes to commercial products in sectors such as water treatment, drug delivery, and sensing.

(6) Computational Modeling and AI Integration
Machine learning algorithms and computational modeling can be employed to predict nanoparticle properties, optimize synthesis conditions, and accelerate the discovery of novel nanocomposite materials.

(7) Circular Economy Approaches
The reuse of agro-waste and industrial byproducts in nanoparticle synthesis should be expanded, aligning nanotechnology with sustainable development goals (SDGs) and minimizing waste generation.

6. Conclusion

This work highlights magnetite nanoparticles and magnetite-based nanocomposites as promising multifunctional materials, offering a combination of superparamagnetic behavior, high surface-to-volume ratios, tunable surface chemistry, and environmental compatibility. The green synthesis method employed demonstrates a cost-effective and eco-friendly approach to producing stable nanomaterials with controlled size and crystallinity, making them suitable for biomedical imaging, targeted drug delivery, catalysis, and environmental remediation. Incorporating biochar and other supports into magnetite nanocomposites further enhances surface activity, thermal stability, and adsorption efficiency, enabling the removal of heavy metals and organic pollutants from wastewater. The diverse applications of magnetite nanocomposites, from medical diagnostics to environmental sustainability—showcase their potential in addressing global challenges. Future research should focus on scaling production, improving surface functionalization, and exploring hybrid nanocomposite systems to further expand their applicability in next-generation nanotechnology-driven solutions.

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