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Magnetic-Field-Guided $Zn_xFe_{2-x}O_3$ Nanoparticles: Design, Model, Synthesis, Characterizations, and Potential Role in Medical Biotechnology

Gizachew Diga Milki*

Abstract

In this research, the nature of the magnetic field guided by $Zn_xFe_{2-x}O_3$ nanoparticles is studied. The research presents a comprehensive view, design, model, synthesis, characterization, and the potential role of magnetic $Zn_xFe_{2-x}O_3$ in medical biotechnology. The research is designed to optimize the size, shape, surface, and composition of magnetic nanoparticles. Herein, multiscale physics models and COMSOL Multiphysics models are employed to model the magnetic, thermal, and stochastic properties of nanoparticles. For the ease of environmental, medical, health, and safety, different synthesis methods are identified. However, greater attention is invested in Hydrothermal, Solvothermal, and Biological (Green) methods. In addition, EDX, X-ray photoelectron emission spectroscopy (XPS), and a high-resolution scanning electron microscope are proven for characterizing Zn-doped α-Fe_2O_3 nanoparticles. For vivo or in vitro study, the biophysical properties of $Zn_xFe_{2-x}O_3$, including biocompatibility, bioreactivity, bio-absorption, bioavailability, and thermal resistance, are envisioned. Moreover, optimizing the magnetic nanoparticles, nanoparticle scaling, surface engineering/coating, and proposing to improve the quality and progress of medical biotechnology. Particularly, the optimization process enables growth and transformation in medical biotechnology and regenerative medicine. Moreover, the study of magnetic and optical properties of $Zn_xFe_{2-x}O_3$ nanoparticles enables enumerating their nanoscale properties, including particle size, and nanotoxicity effects. Optimizing the nanoscale properties of Zn-doped α-Fe_2O_3 in conjunction with nanotechnology enhances research and development in medical biotechnology. To this end, a strategic approach, importantly, streamlining, is proposed to improve multifunctionality and quality of workflow.

keywords: Cell imaging, diagnosis, drug delivery, medical biotechnology, magnetic nanoparticles, magnetic fluid hyperthermia, nanotechnology

INTRODUCTION

The research into magnetic oxide nanoparticles is getting greater attention due to their applications in environmental safety, health, medicine, and biotechnology research. Among the marvel magnetic nanoparticles, emphasis is given to $Zn_xFe_{2-x}O_3$ nanostructures. $Zn_xFe_{2-x}O_3$ is an II–VI diluted magnetic semiconductor that exhibits a tunable band gap and biocompatibility. multifunction, and multiferroicity. It is thermally stable above a temperature of 1000°C, which is the best fit for magnetic fluid hyperthermia. As A. Lassoued (2021) [1] demonstrated, the crystal structure of $Zn_xFe_{2-x}O_3$ is a single-phase rhombohedral (hexagonal) structure with the space group R-3c.

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The crystal structure of this magnetic nanoparticle has a direct impact on biomedical and photocatalytic applications. Magnetic $Zn_xFe_{2-x}O_3$ nanostructures are multifunctional nanomaterials, combining diagnosis and therapeutic processes. This process improves cancer theranostics by combining magnetic resonance imaging, advanced diagnostics, and hyperthermia. As Bhattu M, et al. (2024) [2] revealed, doping and modifying the magnetic properties of magnetic ferites, $ZnFe_2O_4$, with cations, such as Co^{2+}, can directly improve their function in medical biotechnology. It can improve magnetic resonance imaging, magnetic fluid hyperthermia, and maximize its functionality in personalized medicine. As Jyothish B. & Jacob J. (2025) [3] and Nawaz MN, et al. (2025) [4] revealed, doping of zinc ferrite ($Zn_xFe_{2-x}O_3$ or $ZnFe_2O_4$) nanoparticles with Co^{2+} is a promising strategy that can significantly improve its functionality for applications in personalized medicine.

The quest for desirable nanobiosensors, magnetic separation, targeted drug delivery, and immunotherapy increases the demand for magnetic nanoparticles. Due to its thermal stability, biocompatibility, and low toxicity, $Zn_xFe_{2-x}O_3$ is preferred for bioelectronics/telemedicine, medical biotechnology/Regenerative medicine. As Fahim, YA. (2025) [5] revealed, magnetic nanoparticles exhibit programmable and responsive behavior under the influence of external fields, enhancing their utility in drug delivery and cancer treatment based on hyperthermia.

Zn, Fe, and O_2 are highly abundant in the human body. The deficiency of these elements in the body causes various risks and effects on health. Baddam S, et al. (2026) [6] revealed that the deficiency of Zinc (Zn), Iron (Fe), and Oxygen (O_2) can lead to severe cognitive impairment. As the current research inluding Kupta S, et al. (2020) [7], epidemiologically, deficiency of Zn is susceptible to infectious disease, while lack of Fe causes either retards cognitive development or leads to cognitive impairment. Moreover, the deficiency of these nutrients in body cells and tissues is responsible for anemia, oxidative stress, DNA damage, and sometimes cancer. Jeng SS and Chen YH. (2022) [8] revealed that zinc deficiency coexists with iron deficiency and causes anemia.

To unravel health problems related to minerals, nutrition, and epidemic disease, a close look at the potential role of nanotechnology is important. Nanotechnology is indispensable for nanoparticles and nanomedicine. Nanotechnologies as a way of synthesizing, computing, and characterizing magnetic nanoparticles is a pillar of nanomedicine and medical biotechnology. It provides efficient detection, therapeutic, theranostics, and imaging methods that help to mitigate cancers for longer-term treatment. Nanotechnology enables therapeutic and theranostic methods that allow clinicians to control and monitor disease at its earliest stage.

In this research, cutting-edge applications of magnetic nanoparticles, including $Zn_xFe_{2-x}O_3$ nanoparticles in biomedicine and medical biotechnology, are discussed. Hence, the nature of interaction between $Zn_xFe_{2-x}O_3$ nanoparticle and body fluids – such as hemoglobin (Hb) and DNA – is studied. Then, the magnetic and optical properties of magnetic nanoparticles are revitalized. To this end, this research is aimed at investigating the new feature of $Zn_xFe_{2-x}O_3$ nanoparticles and optimizing biophysical properties, such as biocompatibility, sensitivity, and stability, for intended biomedicine and medical biotechnology. More importantly, emphasis is given to the potential role of the stated nanoparticles in diagnostics and treatment of domestic diseases, including cancer, anemia, and thalassemia.

INTERACTION OF $Zn_xFe_{2-x}O_3$ NANOPARTICLE WITH BODY FLUIDS

DNA nanotechnology enables insights into microscopic and nanoscale interactions of nanoparticles. The analyses and modeling of such interactions are the best approach to detect, diagnose, and control many epidemics, such as cancers. DNA Nanotechnology also enables detecting the transmission ways and treatment techniques of epidemic diseases such as tuberculosis, malaria, anemia, Gonorrhea, Ebola, and coronavirus. As a counterpart, DNA nanotechnology enhances genome editing, genomics profiling, next-generation gene sequencing, and proteomics. DNA nanotechnology enables the treatment of chronic disease, including multiple sclerosis, by inducing immune tolerance and facilitating central nervous system repair.

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DNA Nanotechnology studies the phenomenon of nanoparticles' interactions with human body fluids at the gene level. DNA is studied because most viruses contain DNA and RNA, which carry genetic information. However, to fully understand the response of $Zn_xFe_{2-x}O_3$ nanoparticles to the epidemic, it is important to analyze the interaction between the nanoparticles and genetic matter. Based on nanoparticle interaction with DNA and Hb influence, the electrophoretic properties at the interface of double layers. It can significantly help to parameterize the electrophoretic properties and Van der Waals interaction in terms of zeta potential, Gibbs free energy, and Hamaker's constant. As Verma H, et al. (2022) [9] revealed, nanoparticles can also alter DNA sequences and their structures. Consequently, it alters the surface stability, sensitivity, biocompatibility, efficiency, and drug efficacy of magnetic nanoparticles.

The functionality of microfluidic systems is operated based on interaction between magnetic nanoparticles (MNPs) and biomolecules such as DNA & Hb. This interaction is an essential element of lab-on-a-chip (LOC) technologies designed for rapid, automated, and proactive molecular diagnostics. Lab-on-chip technologies based on the interaction between magnetic nanoparticles and DNA can be essentially applicable in PCR, gene sequencing, and diagnostics. Nucleic acid extraction and purification process from cellular contaminants – such as proteins, lipids, and other impurities – incorporates this principle. As Monfaredan A, et al. (2026) [10] revealed, the microfluidic system can be developed to achieve rapid, high-purity, and reliable isolation of cfDNA from blood plasma. Moreover, Microfluidic chips can help to measure the level and concentration of hemoglobin in a blood sample.

In this section, we will explore major interactions between Zn-doped iron oxide nanoparticles with DNA/genes, Hemoglobin (Hb), and physical principles associated with these interactions. Zn-doped iron oxide nanoparticles can generate thermal energy during thermal interaction. It also exhibits nano-electromechanical interactions, electrostatic interactions, and magnetic interactions. $Zn_xFe_{2-x}O_3$ nanoparticles can also interact with DNA, genes, and proteins. This interaction is promising for designing a nanobiosensor. These interactions make $Zn_xFe_2O_3$ nanoparticles a useful material for immunoassays, magnetic fluid hyperthermia, magnetic resonance imaging, Gene therapy, and drug delivery. Immunological functions, including white blood cell circulation, antigen detection by antibodies (immunoglobulins), involve molecular and nanoparticle interactions.

$Zn_xFe_{2-x}O_3$ nanoparticles also experience Van der Waals Interaction. This interaction is a weak interaction between the nanoparticles and genetic matter. It gives rise to resonant dispersion due to covalent bond distortion.

The research of V.N. Nikiforovon et al. (2018) [11] indicates that the magnetic properties of DNA can be demonstrated by a magnetic SQUID magnetometer. It is shown that DNA and doped DNA exhibit paramagnetic and spin-glass. It is expected that the magnetic nature of DNA originates from the intrinsic charge flow along the DNA helix. This magnetism is of Solenoidal and directed orthogonal to the current density. On the other hand, Chang Hoon Lee et al. (2018) [12] verified that the magnetization-magnetic field curve indicates that DNA is ferromagnetic on liquid Helium. However, the possible origin of paramagnetic behavior in DNA is attributed to the charge carrier, specifically electrons, producing circular fields and an induced moment when exposed to an external magnetic field. This idea is useful in the explanation of the interaction of magnetic $Zn_xFe_{2-x}O_3$ nanoparticles with DNA.

Moreover, magnetic nanoparticles can interact with hemoglobin. Zn-doped iron oxide nanoparticles interact with hemoglobin (Hb) by forming non-covalent bonds like electrostatic and hydrophobic interactions. The presence of Zn cation has a significant role in controlling the magnetic nanoparticle interaction with red blood cells and iron magnetic structure (Hb). Shukla RK, et al. (2021) [13] published that the magnetic nanoparticle interaction with DNA and Hb is significantly important in bioconjugation, cytotoxicity, and DNA repair.

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METHODS

Designing Magnetic Nanoparticles

Magnetic nanoparticles can be designed by engineering their size, surface, and composition for specific applications. The design procedure involves the choice of synthesis method, predefining core functions, such as medical biotechnology or personalized medicine, identifying cost-effective and environmentally friendly tools, and the choice of characterization method to ensure stability, biocompatibility, and targeted functionality. Veiseh O. (2010) [14] also presented the essentials of magnetic nanoparticle design based on design criteria such as size, coating, and molecular functionalization.

In the context of medical biotechnology and personal medicine, magnetic nanoparticles are designed at the core-shell level by optimizing biophysical properties such as biocompatibility, stimuli-responsive stability, and specific function. These biophysical properties are seamlessly tailored and guided by an alternating magnetic field. The functionality of magnetic nanoparticles, including drug delivery, fluid hyperthermia, imaging modalities, and immunotherapeutic applications are optimized in the design process.

Modelling Magnetic Nanoparticles

There are a variety of methods for modeling magnetic nanoparticles. Most importantly, analytical, stochastic, and numerical methods are known for simulating magnetization dynamics, surface properties, biophysical interactions, and multifunctionality. As Raouf I. (2020) [15] demonstrates, the Stoner–Wohlfarth model, Langevin dynamics, and finite element methods are suitable for capturing particle behavior in medical applications. In this research, multiscale physical models – such as Green's model and COMSOL Multiphysics models – are emphasized.

Multiscale physics enables us to investigate links between magnetic field, strain, and magnetothermal fluid models that explore the relation between magnetic field and heat. Fiocchi S, et al. (2022) [16] have described the potential of the COMSOL Multiphysics model for core-shell nanoparticles, that combine strain-coupled magnetostrictive and piezoelectric phases. The COMSOL Multiphysics coupling model enables the modeling of a magnetic nanoparticle. As Hewlin, RL. (2023) [17] highlighted, a multiphysic computational model of a magnetic nanoparticle has a potential role in medical drug targeting. Multiphysics coupling models are quite applicable in modelling the response of nanoparticles to magnetic field, strain, piezoelectricity, light, and heat. As Li J, et al. (2019) [18] revealed, by validating numerical results in comparison to experimental data, the COMSOL Multiphysics model can enable optimizing magnetic field intensity and scaling nanoparticle dose.

Moreover, we model magnetic nanoparticles (MNPs) by encapsulating the magnetic core as a functional material and coating them with silicates, polymers, or CNTs. Moreover, the magnetic properties of the nanoparticle are modeled by the 3D Heisenberg model. As Du Z, et al. (2020) [19] and Reeves DB, et al. (2014) [20] verified, the Fokker–Planck equation accurately describes AC magnetization dynamics of magnetic nanoparticles (MNPs) while the Langevin approach demonstrates the stochastic dynamics of MNPs.

In advance, magnetic nanoparticles can be modelled using multiscale models, typically a multiscale Green's model. As Chand K, et al. (2025) [21] noted, Multiscale Green's model enables the precise and efficient design of nanostructures. As Sun C, et al. (2008) [22] predicted, the functionality of magnetic nanoparticles in medical biotechnology requires multi-scale modeling that integrates the nanoscale material properties in an applied alternating magnetic field. In some cases, an alternating magnetic field is employed to guide magnetic nanoparticles.

These models can enhance magnetic nanoparticles for magnetic fluid hyperthermia, Photodynamic therapy, and drug delivery systems. As Wang S, et al. (2014) [23] revealed, multiscale physics models can be used to study the drug delivery of magnetic nanoparticles by an external ambient magnetic field.

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Moreover, it helps to optimize treatment protocols such as real-time analysis, standardizations, specific procedures, medications, and procedures for medications and medical research.

The functionality of magnetic nanoparticles is the result of a variety of property measurements. These measurements are concerned with magnetic nanoparticles (MNPs) sizing, crystal size, surface area, and the surface area to volume ratio. It also involves manipulating and determining the core size of $Zn_xFe_{2-x}O_3$ nanoarticles, measuring hydrodynamic size, and the size of coatings, such as chitosan, CNT, hydrogels, etc., that improve its functionality in imaging, hyperthermia, and theranostic medicine. This measurement is done by Dynamic Light Scattering (DLS) for hydrodynamic size, Transmission Electron Microscopy (TEM) for core size, vibrating sample magnetometry, and Magnetic circular dichroism for determining magneto-optical effects. This process can verify the magnetic states, surface absorption, particle scattering, stability, and biocompatibility. In the subsequent section, some of the effective synthesis methods and characterization techniques are discussed for magnetic nanoparticles.

Synthesis Methods

Different methods have been used to synthesize magnetic nanoparticles. As Majidi S, et al. (2016) [24] reported, several methods including co-precipitation, microemulsion, thermal decomposition, solvothermal, sonochemical, microwave-assisted, chemical vapor deposition, combustion, carbon arc, and laser pyrolysis, have commonly been used for the synthesis of magnetic nanoparticles. Moreover, biological methods or green synthesis methods are seen as eco-friendly, cost-effective, and practically advisable for biomedical applications. These methods are mostly used because they present enhanced biomedical and biophysical properties of the $Zn_xFe_{2-x}O_3$ nanoparticles. In this research, greater emphasis is given to the Solvothermal method and biological (green) synthesis method due to their biofunctionality, economic importance, and product quality. Besides, the biological synthesis method of $Zn_xFe_{2-x}O_3$ nanoparticles is mostly promising since it is cost-effective, eco-friendly, and an alternative way for discovering medical materials. Hence, the two synthesis methods are presented one by one:

Solvothermal Method

The solvothermal method is a versatile, high-pressure, and high-temperature technique engineered to synthesize nanoparticles with high-quality, crystalline, and uniformity. It is applicable in the synthesis of metals, metal oxides, metal-organic frameworks, and magnetic nanoparticles by heating precursors within a non-aqueous, organic solvent inside a sealed vessel. As Mukherjee S, et al. (2018) [25] noted, the solvothermal method is also applicable for the synthesis of nanowires with high grades.

Solvothermal synthesis of magnetic nanoparticles, such as $Zn_xFe_{2-x}O_3$ ferities, involves heating metal precursors in organic solvents, typically polyethylene glycol (PEG). It is undertaken within a sealed autoclave at a temperature of nearly 200°C. This synthesis method maintains high crystallinity and monodisperses particles with a size in the nanometer scale. This technique allows precise controlling the size, shape, and magnetic properties, including saturation magnetization, *coercivity* (magnetic hardness/softness), and optical properties.

The solvothermal method is used to synthesize both elemental and compound nanostructures. It takes place in an autoclave and involves chemical reactions at extreme temperatures and pressures. Haloing Hu et al. (2020) [26] pointed out that the simple solvothermal method has been proven to be an excellent route to synthesize iron oxide nanorods. The solvothermal method for synthesizing Zn-doped iron oxide nanoparticles involves reacting iron and zinc precursors in a solvent within a sealed, high-pressure autoclave. The procedure involves dissolving the precursors, such as iron chloride and zinc acetate, in either ethanol or deionized water, heating the mixture in an autoclave under specific temperature and pressure conditions for a set time, and then cooling, magnetic separating, and drying the final product. The mechanical properties, such as size, shape, crystal morphology, and biophysical properties, are influenced by the specific temperature, solvent, and precursor concentrations. As Shaterian M, et al.

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(2019) [27] demonstrated, solvothermal synthesis is a versatile technique to create nanoparticles with customized size and structure, which improve magnetic and catalytic applications.

Not only Zn-doped iron oxide nanoparticles but also more complex transition metal, alkaline metal, and rare earth metal-doped iron oxide compounds can be synthesized by the solvothermal method. As a prime example, A. Manohar C. Krishnamurthy (2017) [28] synthesized $Mg_{1-x}Zn_xFe_2O_4$ with (x = 0.2, 0.4, 0.5, 0.8) by the Solvothermal flux method. Hence, upon Mg and Zn doping, the resulting crystal appears cubic spinal structures. Reviews of Lagerkvist U, et al. (2016) [29] also discussed the possibility of preparing single-phase ZnO (0% Fe), $ZnFe_2O_4$ (67% Fe), and α-Fe_2O_3 (100% Fe) using nitrates and acetate precursors.

The steps for the Solvothermal method of synthesizing $Zn_xFe_{2-x}O_3$ nanoparticles are illustrated in Figure 1.

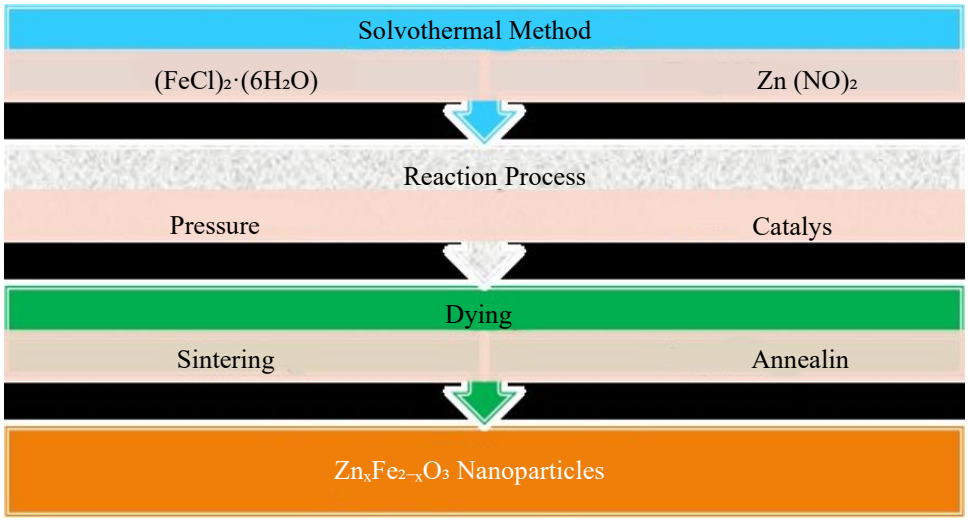


Figure 1. Synthesis of $Zn_xFe_{2-x}O_3$ nanoparticles by the solvothermal method.

A typical catalyst used in the synthesis process is sodium acetate (Ch_3COO–Na), urea, and polyethylene glycol (PEG). These catalysts impact crystal morphology because they behave as reducing and stabilizing agents, while sodium acetate/ or potassium acetate serves as a stabilizing agent. It is mainly applied for the synthesis of $Zn_xFe_{2-x}O_3$ and metal nanoparticles, such as Au or Ag, which are candidates in biomedical applications. The Zn-doped iron oxide prepared in this way exhibits different magnetic properties. These properties with proper thermal conditions enable $Zn_xFe_{2-x}O_3$ nanoparticles for the applications of biomedicine, magnetic recording materials, gas sensors, and catalysts.

Biological Synthesis of $Zn_xFe_{2-x}O_3$ Nanoparticles

The biological method, also referred to as the green synthesis method, involves the utilization of bacteria, viruses, leaves, fruit, roots, and domestic waste such as peels. The green plants, such as Astragals membranous, Tephrosia Purpurea, Taxus brevifolia, and magnetotactic bacteria, are used as: (1) a source of metal/metal oxide nanoparticles, (2) used for developing new immunity, (3) are themselves antibiotics and anticancer, and (4) increase the crystallinity. In this section, the biological method of synthesizing magnetic nanoparticles is illustrated in Figure 2.

Adding NaOH or NH_3 is essentially important since it is a precipitating agent as well as regulate PH level. Hence, adding NaOH enables rapid formation of $Zn_xFe_{2-x}O_3$ nanoparticles and control of crystal size as well as crystal uniformity. Moreover, it enables the hydrolysis of cations and serves as a stabilizing agent.

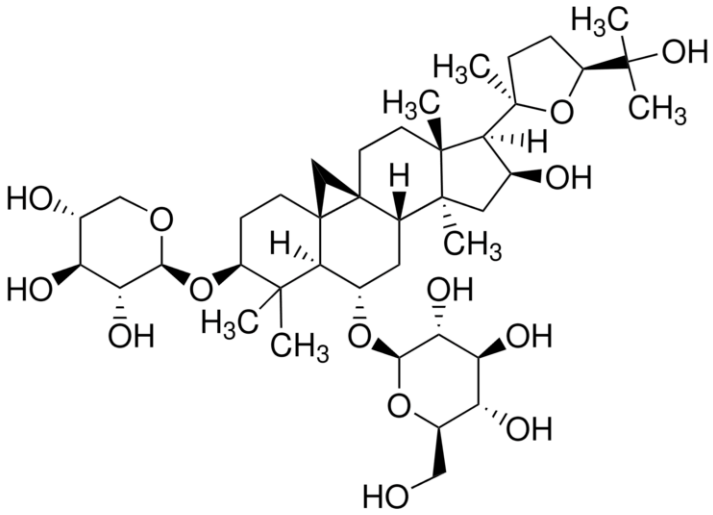
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(a) Illustration 1: Astragalus Plant root



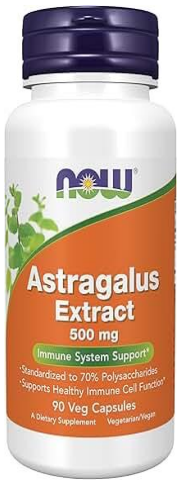
(b) Illustration 2: Grinded Astragalus root



(c) Illustration 3: Chemical formula and structure



(d) Illustration 4: Mixing Powder with distilled water and heating.



(e) Illustration 5: Filtered Powder.

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(f) Powered astragalus root.



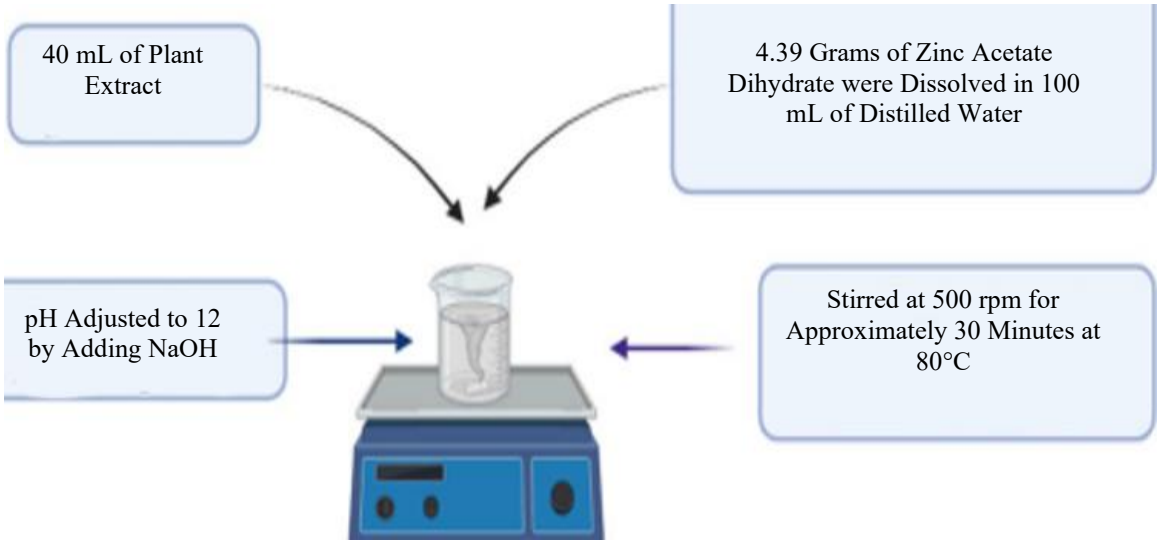
(g) 3Zn $(NO_3)_2$.



(h) Iron powder, 2Fe(s) Illustration 6: Mixing process.



(i) Illustration 7: Stir and heat the mixture.



(j) Illustration 8: Adding precipitates, NaOH/or NH_3.

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(k) Illustration 9: Drying and calcinating ZnO/Fe_2O_3.

Figure 2. The synthesis of $Zn_xFe_{2-x}O_3$ nanoparticles using Astragalus leaves and $3Zn(NO_3)_2$ and Fe precursor.

Yang S, et al. (2017) [30] were able to synthesize Zn (II)-doped magnetite nano rings of width 13–20 nm from leaf extract. $Zn_xFe_{2-x}O_3$ can also be synthesized from Magnetotactic bacteria because it is enriched with Iron oxide nanoparticles. The nanoparticles synthesized in this way are characterized by magnetic resonance or electron paramagnetic resonance. In the context of this research, $Zn_xFe_{2-x}O_3$ Nanoparticles prepared by the green or biological method have the least toxic effects. It has a few drawbacks related to scalability and monitoring reaction temperature. Nanoparticles synthesized from the astragalus plant (leaf, stem, and root) are pollution-free, cost-effective, and have high grades. When optimized properly, the biological or green synthesis method is regarded as safe and recommended for medical applications.

Characterization Methods

Characterizing magnetic nanoparticles involves comparing the physical properties, such as size, shape, crystal structure, and crystal morphology, to ensure desired and reliable functionality. As Stiufiuc, GF. (2024) [31] revealed, precise characterization of magnetic nanoparticles ensures reproducibility of results and optimizes properties like superparamagnetism, saturation magnetization, and biocompatibility. The biomedical application of magnetic nanoparticles is not only influenced by preparation, design, production modalities, and biophysical properties but also by characterization methods and processes. Therefore, it is also important to look toward a reliable, high-grade, and cost-effective characterization method.

Advanced Nanoscale characterization techniques allow observing the location and distribution of magnetic ions, size, nature of dopants, and defect states. As Somayeh Shams (2021) [32] experimentally verified, Zn-doped Fe_2O_3 can be characterized by XRD, SEM, FTIR, UV–Visible spectroscopy, and VSM. In addition, Kouhpanji MRZ, et al. (2020) [33] characterized magnetic nanoparticles by subtracting isothermal remanence and DC demagnetization curves. This technique, referred to as the remanence curves technique, is performed by comparing the results with the Stoner–Wohlfarth model. According to M. Sharmila et al. (2022) [34], the morphology of Zn-doped iron oxide can be characterized by Field Emission Scanning Electron Microscope (FESEM) and Energy Dispersive Spectroscopy (EDS. The crystal structure of the compound can also be characterized by X-ray diffraction, Neutron diffraction, Raman spectroscopy, and X-ray photoelectron emission spectroscopy (XPS). These characterization techniques not only influence the crystal structure but also nanosize and physical properties. For example, the X-ray photoelectron emission spectroscopy (XPS) at the Fermi level demonstrates the metallic characteristics of $Zn_xFe_{2-x}O_3$. In this research, EDX, XPS, and HRTEM are further discussed.

Energy Dispersive X-ray (EDX)

X-rays are electromagnetic waves that have a finite wavelength. This wavelength is essential for characterizing magnetic nanoparticles (MNPs) because it is comparable to atomic spacings within the crystal lattice. This equitable wavelength allows a precise structural, chemical, and magnetic analysis

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of magnetic nanoparticles. It is also useful in the study of drug delivery, in which the EDX is an important tool to detect nanoparticles. The Energy Dispersive X-ray (EDX) is a technique of elemental analysis associated with electron microscopy based on the generation of characteristic X-rays. The finite element analysis methods, aided with energy dispersive X-ray analysis, can detect nanoparticles embedded in body tissues. Joan Talibaw et al. (2022) [35] characterized hydrothermally synthesized Zn and Ni co-doped hematite by Zeiss Crossbeam, which is connected directly with energy-dispersive X-ray spectroscopy (EDS). The research of Krishnaveni K., et al. (2018) [36] also show that XRD analysis of Zn-doped IONPs is in the hematite phase with rhombohedral structure. The resulting nanoparticle shows crystal homogeneity and uniformity. Besides, magnetic nanoparticles can absorb UV light in the visible electromagnetic spectrum. Microanalysis of these nanoparticles using EDX can help to detect metal contaminants in lung cancer. Moreover, it enables detecting the antibacterial and antimicrobial activity of Zn-doped iron oxide (hematite).

X-ray Photoelectron Emission Spectroscopy (XPS)

X-ray Photoelectron Spectroscopy (XPS) is a modern technique of chemical analysis. It is used to determine compositions, constituents, and chemical structure by irradiating the sample with monochromatic X-rays. These techniques enable emissions of energetic photoelectrons with a characteristic frequency. X-ray photoelectron spectroscopy enables measuring the Kinetic energy of emitted electrons, which also helps to determine the temperature. The XPS core level and valence band (VB) photoemission spectra can help to describe the degree of iron oxidation. This is of fundamental importance for better understanding the electronic structure of the magnetic nanoparticles to control and improve their quality for specific biomedical applications.

The morphological evolution of nano rings can also be achieved from nano plates by a combined effect of decomposition of the organic component and diffusion of growth of the nanocrystals. X-ray photoactive superlattices of $Zn_xFe_{2-x}O_3$ can be prepared on a silicon substrate. In the case of iron-doped ZnO, the band gap decreases from 3.24 eV to 3.01 eV. However, in the case of Zn-doped iron oxide, the band gap increased from 3.24 to 3.32 eV since the atomic and ionic radius of Fe is greater than that of zinc (Figure 3). The difference in energy between Photon energy and optical band gap near the high absorbance region is given by Tauc and the Davis–Mott model:

$$ahv = B(hv - Eg)\exp(n) \quad (1)$$

where α – is the absorbance coefficient, β is a constant, h is the Planck constant, and v is the Photon frequency.

X-ray photoelectron spectra and optical property analysis determine valence bands, which indicate a shift in the Fermi level characteristic of a conversion from n-type in pure α-Fe_2O_3 to p-type with relaxation time less than 10 s zinc-doped α-Fe_2O_3. The data confirmed by X-ray photoelectron spectroscopy (XPS) shows that incorporation of Zn at the Fermi level increases the density of states (DOS).

High Resolution Transmission Electron Microscopy (HRTEM)

HRTEM is an imaging mode of a specialized transmission electron microscope that allows direct imaging of the atomic structure of samples. It has high resolution in analyzing and characterizing metal nanoparticles, magnetic oxide nanoparticles, semiconductor nanoparticles, and nanotubes. The interference of the electron wave in the image plane produces high contrast. It is also used in phase contrast transmission electron microscopy.

The working principle of a high-resolution transmission microscope (TEM) depends on the biocompatibility of the molecules or nanoparticles. TEM can perform the characterization process more rapidly with three different accelerating voltages. Thus, it can produce good image viability and contrast. It can be combined with Electron Energy Loss Spectroscopy (EELS) to characterize the electrical and optical properties of magnetic nanoparticles. It is also used to determine the lattice parameters of nanocrystals.

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By measuring the atomic form factors, atomic plan, and interplane spacing, the lattice parameters of Zn-doped iron oxide can be measured.

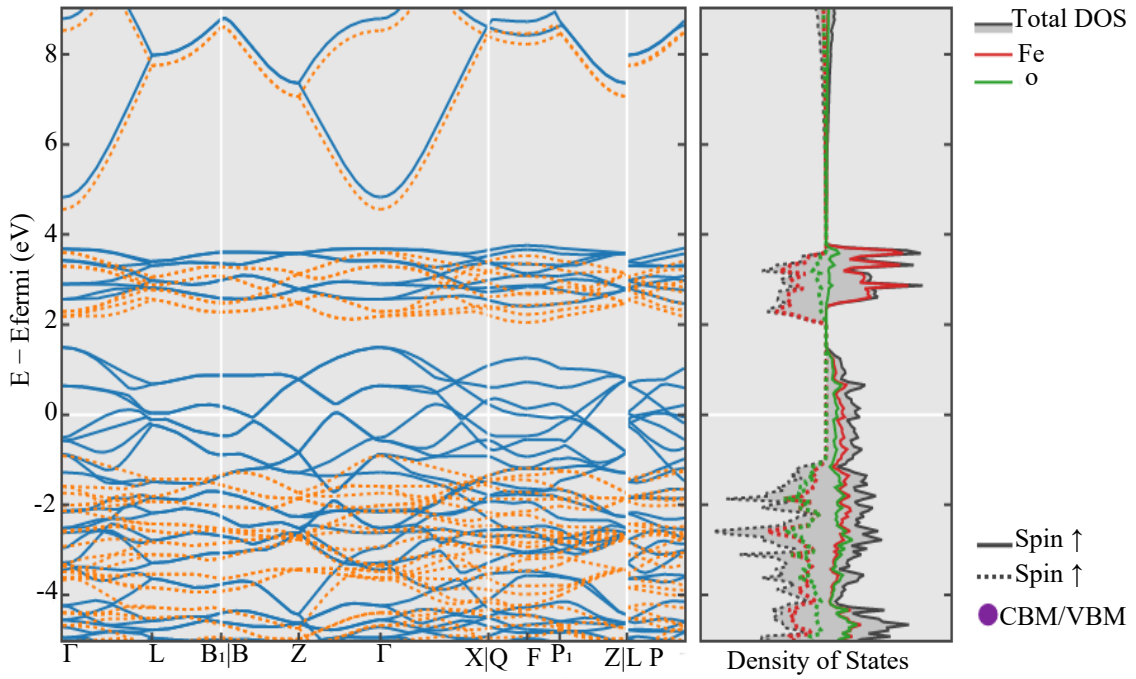


Figure 3. Energy band gap structure and density of states.

As Manish Kumar et al. (2019) [37] using a high-resolution transmission electron microscope observed, the average crystallite size of Zn-doped iron oxide nanostructure is 20 nm. S. Ghosh and RN. Basu (2019) [38] verified that HRTEM can also be used for characterization of core-shell type metal oxide-coated noble metal particles, multimeric nanoparticles, and asymmetric nanoparticles for applications in photo-catalysis, photo-thermal therapy, molecular sensing, and photovoltaics. Cameras are connected to this device to record events and image resolution. In general, characterizing Zn-doped Fe_2O_3 nanoparticles with XRD, EDX, SEM, FTIR, and HRTEM increases crystal quality, homogeneity, reduces grain size, and increases phase purity.

MAGNETIC PROPERTIES OF $Zn_xFe_{2-x}O_3$ NANOPARTICLES

Different aspects of magnetic nanoparticles studied here make an intuitive discussion of the impact of their properties, synthesis route, design, models, and characterization methods for biomedical applications, including medical biotechnology, regenerative medicine, and personalized medicine. The study of magnetic property revealed that $Zn_xFe_{2-x}O_3$ nanoparticles and its nanocomposite exhibits superparamagnetism. By taking the dopant ion, x = 0.4 and varying it up to 1, its superparamagnetic phase is attained. To improve the resonance imaging and magnetic fluid hyperthermia, $Zn_xFe_{2-x}O_3$ Nanoparticles are guided by an AC magnetic field. This is because the external magnetic field helps in tuning resonance and Larmor frequency for ferromagnetic resonance imaging. In addition, the existence of ferromagnetism at Curie temperature is studied by the 3D Heisenberg Model. Unlike carbon nanotube, Graphene, and fullerene, which typically produce toxic effects, carbon monoxides and carbon dioxides, magnetic oxides, like $Zn_xFe_{2-x}O_3$, do not produce toxic effects. Here, a streamlined strategic approach is employed to unravel the nanotoxicology, real-time analysis, and increase the access quality. These chronological advancements are presented in the subsequent section.

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Magnetic $Zn_xFe_{2-x}O_3$ nanostructures exhibit different properties. Most importantly, it exhibits pronounced biophysical and surface properties. $Zn_xFe_{2-x}O_3$ nanostructure particles adopt a spinel or hematite structure (rhombohedral) depending on the Zn concentration and synthesis route. It also exhibits high biocompatibility, bio-sensitiveness, and biostability. These properties are responsible for its high interaction with human blood, particularly hemoglobin. It can interact with DNA and form a hybrid nanocomposite. This type of hybrid nanocomposite has been proven to be anticancer. Due to its low toxicity, it is suitable for in vivo and in vitro applications. $Zn_xFe_{2-x}O_3$ serves not only as a medical treatment but also improves the efficiency of hemoglobin for transport. $Zn_xFe_{2-x}O_3$ nanocomposite can be encapsulated into 3D DNA Structures and assembled with nanoscale biodegradable polymers for efficient drug delivery. These properties make $Zn_xFe_{2-x}O_3$ nanostructures quite suitable for nanomaterials in medicine and nanobiosensors. In addition, the compatibility of Fe_2O_3 can be increased by doping with Zn, Co, Mn, and C.

The magnetic properties of diluted magnetic semiconductors – such as $Zn_xFe_{2-x}O_3$ – are related to their intrinsic properties, including structural, surface reactivity, electrical, optical, and magnetic states. Optimizing their properties enables tailoring $Zn_xFe_{2-x}O_3$ naoparticles for synergistic antimicrobial application. In this section, the magnetic properties of biphased $Zn_xFe_{2-x}O_3$ or ZnO/Fe_2O_3 nanoparticles are discussed in detail. This is due to the fact that most of the biomedical applications of these nanoparticles, particularly magnetic resonance imaging, magnetic fluid hyperthermia, and even magnetic separation techniques, are greatly influenced by their magnetic properties.

Thermally, magnetic $Zn_xFe_{2-x}O_3$ nanoparticle exhibits a Curie temperature up to 600 K. They exhibit ferromagnetic properties at every Curie temperature, depending on the amount of dopant. $Zn_xFe_{2-x}O_3$ nanoparticles are soft magnetic nanomaterials with high saturation magnetization and possess low coercivity. Theoretically, the magnetic properties of $Zn_xFe_{2-x}O_3$ nanoparticle are determined by simplified models, including the 3D Heisenberg model. The model describes magnetic interaction in terms of dipole–dipole interactions, magnetic spin interaction, and exchange integral. Assessing these theorems and characterizing their intrinsic magnetic properties, such as spin density of states, the effective magnetic field is expressed by the simplified model. Hence, the relation between effective magnetic field, mean magnetization, and exchange integral is expressed by the Hamiltonian of the system, as shown in Equation (2) below:

$$H = 2J_{ij} \sum \langle S_i \rangle \langle S_j \rangle \tag{2}$$

where H is the Hamiltonian of the system, $\langle S_i \rangle$ and $\langle S_j \rangle$ are mean magnetizations located at site I and j, and J_{ij} is the exchange energy or exchange integral. In the mean field or molecular field theory, the spontaneous magnetization is the second-order phase transition. Mean field approximations give accurate results when higher dimensions are considered, and hence, are suitable approximation methods when anisotropic effects are considered. In the absence of an external magnetic field, the Hamiltonian system of particles in electric interaction does not contain spin operators.

It is visualized that both α-Fe_2O_3 and Zn-doped α-Fe_2O_3 exhibit different magnetic phases. The magnetic property study by Castellanos-Rubio I, et al. (2021) [39] revealed that $Zn_xFe_{2-x}O_3$ shows hysteresis magnetization at Curie temperatures of 5K and 300 K. Most dominantly, it exhibits superparamagnetic phases due to superexchange, ferromagnetic phases arising from double exchange, bound magnetic Polaron, RKKY interactions, and quantum confinements. The ferromagnetic behavior is also expected from anisotropic effects.

The effect of a magnetic field is to alter the direction of spin magnetic moments. In the absence of a magnetic field, the spin magnetic moments are non-uniform and distributed evenly. However, applying

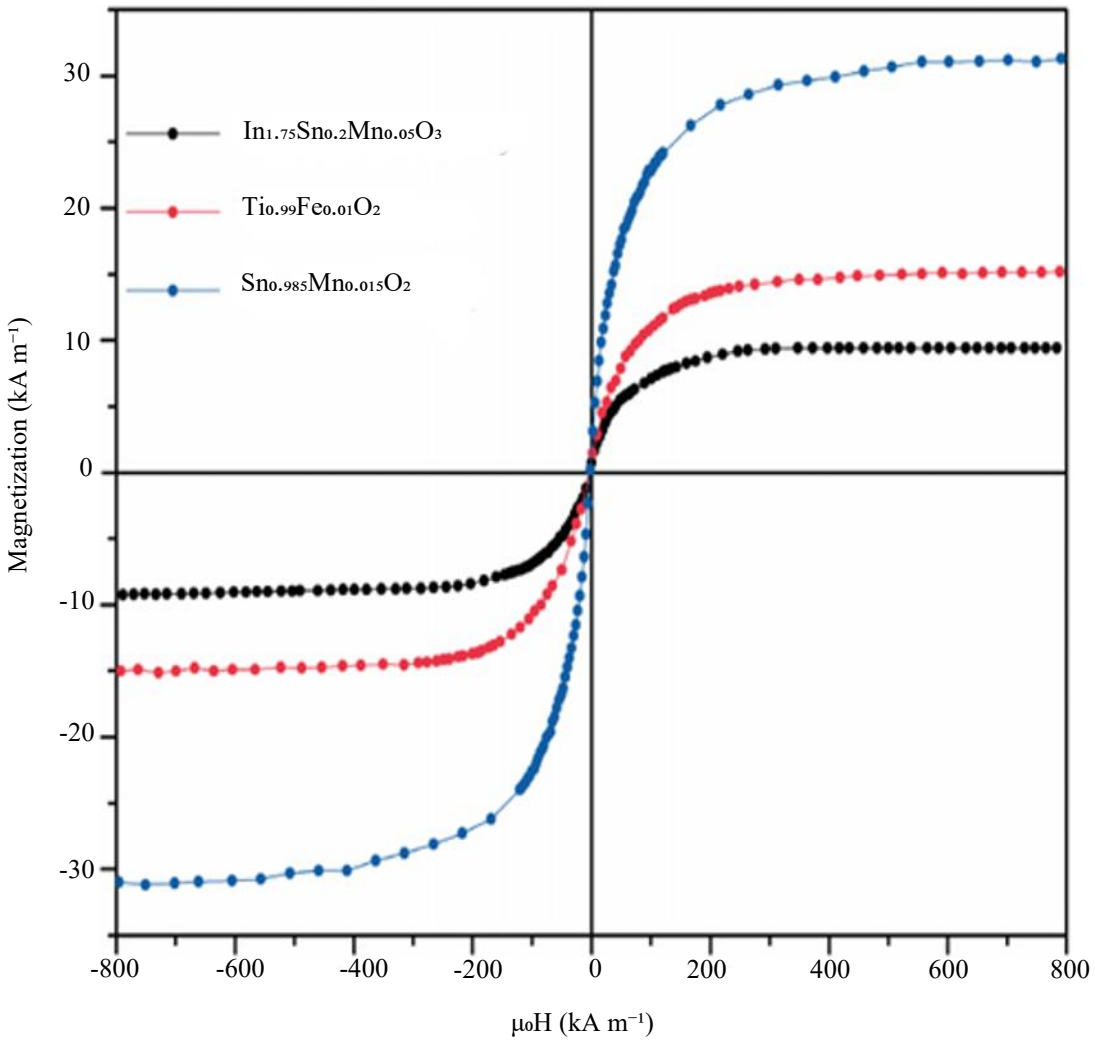
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a magnetic field will make the alignment of spin moments in the same direction, giving rise to strong magnetism. This property is a peculiar characteristic of ferromagnetic nanomaterials.

As shown in Figure 4(a), the relation between magnetization and varying magnetic fields for transition metal-doped Fe_2O_3 is illustrated, and Figure 4(b) illustrates Magnetization vs Magnetic field for Zn-doped Fe_2O_3.

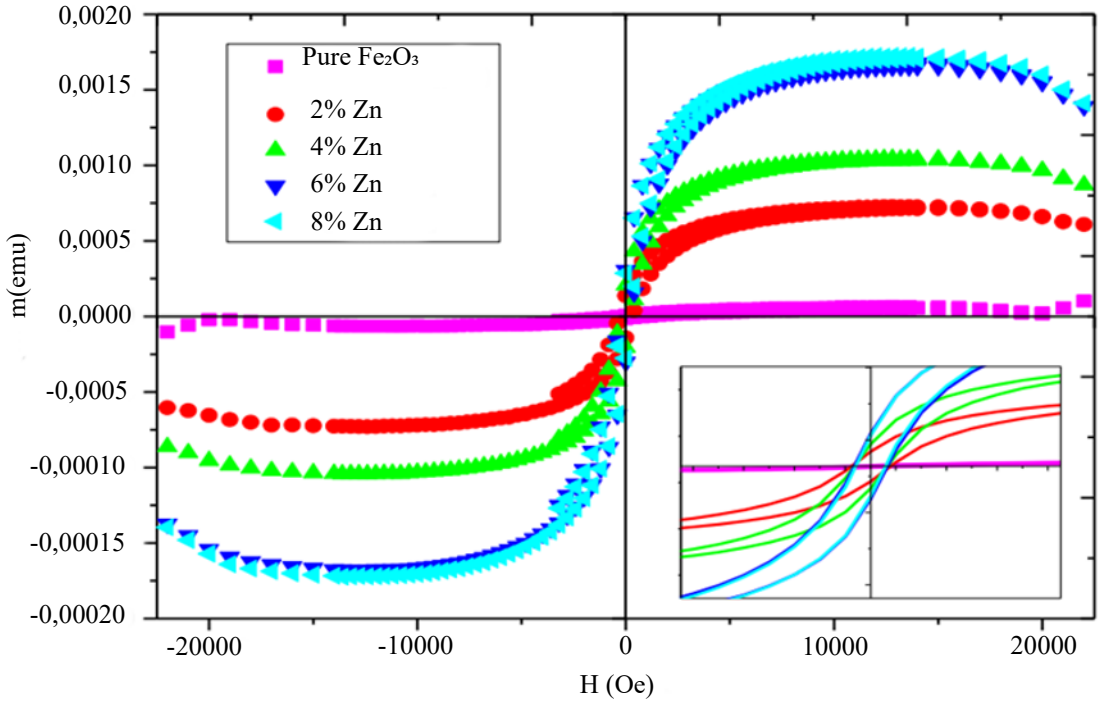
As illustrated in Figure 4, transition metal dopant ions are ferromagnetically coupled with metal oxide. This coupling enhances spin polarization at 300 K. However, it is predicted that $Zn_{1-x}Fe_{2-x}O_3$ can exhibit a Curie temperature up to 600 K. As depicted by Karmakar D, et al. (2007) [40], $ZnFe_2O_4$ spinal ferrite exhibits a phase transition from ferromagnetic to paramagnetic above 450 K.

Zahra Rezay Marand (2013) [41] observed that $Zn_xFe_{3-x}O_4$ nanoparticles prepared by the Co-precipitation method exhibit superparamagnetic properties at room temperature. It also exhibits a high level of saturation magnetization, nearly 74.60 emu/g for x = 0.04. Another research by A Taufiq et al. (2018) [42] shows that the saturation magnetization (Ms) of $Zn_{0.2}Fe_{2.8}O_4$ powder and ferrofluid are 33.530 ± 0.040, and 1.263 ± 0.003 emu/g, respectively. Moreover, Wojciech Szczerba et al. (2016) [43] found that iron oxide nanoparticles synthesized by the same method exhibit maximum saturation magnetization caused by non-magnetic ion (Zn^+) doping.



(a)

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(b)

Figure 4. (a) Magnetization vs magnetic field of TM-doped Fe_2O_3. (b) Magnetization vs Magnetic field Fe_2O_3 for different values of Zn dopant.

STRATEGIES FOR USING MAGNETIC NANOPARTICLES IN MEDICAL BIOTECHNOLOGY

Tailoring magnetic nanoparticles for biomedical applications is a tedious and multi-step process, due to ease of quality, minimizing nanotoxicity, and stability. To this end, the driving force in transforming magnetic nanoparticles for medical applications is detecting, testing, and surface engineering. The process will enhance biocompatibility, stability, and precise control of biophysical properties, including size, shape, and response to rheological conditions such as viscosity, magnetic field, heat, etc.

To ensure such a requirement, designing clear, reliable, and measurable strategies is important. Thus, a streamlined approach in conjunction with a streamlined workflow is proposed. The proposed strategies are then combined to ensure both the high-level strategy (approach) and the day-to-day execution (workflow) to maximize efficiency. These strategies are expected to improve functionalization, monitoring, scaling, optimizing magnetic nanoparticles, and surface engineering for the proposed medicare application and access quality. In the succeeding section, these strategies are discussed in detail in the context of medical biotechnology and personalized medicine.

Optimizing the Functionalization of Magnetic Nanoparticles

Optimizing the functionalization of magnetic nanoparticles (MNPs) involves a multi-step procedure focused on controlling size, stability, and surface crystallography to enhance performance for specific applications like drug delivery or diagnostics. The process typically involves synthesizing a magnetic core, typically Fe_3O_4, coating it with a protective, functionalizable layer with silica, SiO_2, and modifying it with targeting or functional ligands. Here, the functional ligands, including biopolymers, dopamine, oleic acid, silane, etc., are tailored to enhance stability, biocompatibility, and improve dispersibility, primarily for binding molecules for enhanced biomedical and catalytic applications.

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Doping, surface coating, resizing, and optimizing the biocompatibility of magnetic nanoparticles greatly improve medical biotechnology and personalized medicine. It increases drug delivery, drug release, cell viability, bioimaging, molecular diagnosis, precision, immunotherapy, and hyperthermia.

Scaling and Particle Sizing

Magnetic nanoparticles can be manipulated by using time-varying magnetic fields. By using optimum AC magnetic fields, $Zn_xFe_{2-x}O_3$ nanoparticles can be manipulated. When magnetic nanoparticles are exposed to alternating magnetic fields, the nanoparticles with spin will flip in a random direction. In this way, magnetic nanoparticles can induce heat energy sufficient for magnetic fluid hyperthermia/cancer therapy. This process is essentially important in tissue generation, as drug kinetics are stimulated by induced heat energy.

Not only manipulation, but scaling is a vital factor in manufacturing pharmaceutical medicine. It maximizes production from small-scale nanoparticle production to large-scale nanoparticle production. This strategy is a key element to address drugs with the least supply, unravel health care challenges, and reduce wastage. Scaling is primarily focused on formulating a theoretical framework designed to determine the magnetic properties and maximize productivity. It is also concerned with choosing appropriate synthesis methods and procedures that maximize nanoparticle production, quality, and functionality for the ease of laboratory utility to large-scale industry. Consequently, scaling realizes safety, and quality of nanoparticle/drug production, regulatory approval, standardization, and increases commercial visibility. Therefore, scaling magnetic nanoparticles maximizes the demand, commercial viability, and precision of medical biotechnology in the global market.

Monitoring with a Magnetic Field

Magnetic nanoparticle monitoring is a mechanism of systematically measuring, modeling, characterizing, and transforming it for use to maximize productivity and quality. It is concerned with tracking the location, concentration, and physical properties. The most reliable physical properties involve measuring and monitoring temperature, transition states, binding energy, size, dimension, particle distribution, and crystal morphology. This process is essentially important in identifying the impacts of magnetic nanoparticles on health, including breathing, the respiratory system, toxicity, and environmental impact such as pollution. It is also an initial step for designing research on the long-term impact of magnetic nanoparticles in health, medicine, and medical biotechnology.

Magnetic nanoparticles (MNPs) can be monitored by a variety of techniques, including magnetic particle imaging (MPI) and magnetic resonance imaging (MRI) for in vivo tracking, AC biosusceptometry for real-time monitoring in the bloodstream, and thermal noise magnetometry (TNM) or scanning electron microscopy (SEM) for in vitro characterization. More essentially, microfluidic systems integrated with bioelectronics and biochips can perform rapid genetic analysis, to create a sensitive analytic platform and test for hemoglobin and DNA. Monitoring magnetic nanoparticles, for example, by an AC magnetic field, is critically important in optimizing the magnetic properties of magnetic particles for biomedical engineering, medical biotechnology, and biomedicine. The specific method chosen depends on whether the goal is to be tracked in a biological environment or to analyze physical properties in a lab setting.

Surface Engineering, Coating, and Doping

Surface coating is a key step in modifying the biofunctionality of magnetic nanoparticles. Coating $Zn_xFe_{2-x}O_3$ nanoparticles and nanocomposites with Chitosan, CNT, and Silica increases the biocompatibility, thermal stability, and crystal structure. Consequently, surface coating and engineering of Zn-doped iron oxide nanopraticles and optimizing its bio-physical properties will increase its bioavailability, cell separation, diagnostic & therapeutic capability. Optimum doping of $Zn_xFe_{2-x}O_3$ nanoparticle with Co^{2+} can influence its biophysical interactions. More importantly, cobalt-doped zinc ferrite nanoparticles have a significant effect on the cytotoxicity towards lung benign cells and exhibit high cell

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viability in normal cells. As Yu MK, Park J, and Jon S. (2012) [44] revealed, in the theranostic systems, surface engineering strategies can improve biomedical applications of nanoparticles. Moreover, Friedrich RP, et al. (2021) [45] published that surface coating and functionalization of iron oxide nanoparticles can improve their versatility and broad applicability. As Koksharov YA, et al. (2022) [46] revealed, coating can release therapeutic molecules from the drug carrier, reducing the pharmacokinetic dependence of the drug on concentrations of magnetic nanoparticles. Iron oxide nanoparticles coated with CNT can improve tissue re-epithelialization, wound healing, and antibacterial activity. Moreover, Zn-doped iron oxide nanoparticles are quite suitable nutrients for collagen synthesis.

Surface engineering and coating are one of the strategic approaches to minimize the toxicity of magnetic nanoparticles (MNP). Surface engineering of magnetic $Zn_xFe_{2-x}O_3$ nanoparticles modifies surface properties, such as biocompatibility, ion dissolution, and particle agglomeration, that reduce toxicity. Surface coating with polyethylene glycol (PEG), chitosan, or dextran, controlling size and shape, regulating surface charge density, can improve the stability of nanoparticles. Surface coating acting as a protective barrier also minimizes nanotoxicity by preventing reactivity of the metal core, particle aggregations, and agglomerations. Consequently, surface coating/or engineering and doping improve the particle quality, biocompatibility, increase its functionality, and safety. Surface coating/engineering increases the use of magnetic nanoparticles in Opsonization process, an immune process where pathogens including bacteria are coated with proteins, like opsonins or antibodies, to make it biomarker. This process enables an efficient destruction of phagocyctes that engulf a cell.

Streamlining Access

Although the use of nanoparticles, as discussed in this paper, is efficient and reliable for medical treatment, it is important to ensure uniform access and an easy management system. Moreover, being aware of the policies and ethics concerning the dose, injection methods, and safety rules is a key step in streamlining the process. To meet such requirements, streamlining strategies are incorporated in the Medical Biotechnology process and procedures.

Streamlining in medical process and procedure involves designing an easier and simpler system that enhances rapid and real-time data analysis with the greatest prospect. It is aimed at improving the speed, efficiency, and cost-effectiveness of research and development. As Rarokar N, et al. (2024) [47] discussed, streamlined magnetic nanoparticles are increasingly used for a comprehensive, multifunctional theranostic system. Ultimately, these strategies are inevitably used for targeted drug delivery, magnetic hyperthermia, imaging contrast agents, management, and evaluation systems. Streamlining is essentially designed for good manufacturing products, including cells, tissues, and tissue culture.

Streamlining procedures are usually assisted by digital and 3D printing technology. Digital and print technology enable a multiplexed analysis and imaging system. Consequently, it increases the quality and quantity of the packages. In the context of medical biotechnology analysis, streamlining strategies relies in facilitating research and development, optimizing clinical trials, initiating good manufacturing practices, and merging nanotechnology and AI with biomedical processes. These strategies can inevitably improve realtime analysis of biological data, drugs, tissues, and biopharmaceuticals. It also enables optimization of cells for research, regenerative medicine, predicting patients' treatment outcomes, and medical biotechnology.

The quality and performance of biomedical procedures are concerned with the optimization of every procedure, beginning from synthesis, functionalization, scaling, and characterizing biophysical properties. The right of streamlining involves integrating synthesis, scaling, characterization, and functionalization. Ultimately, these processes are aimed at reducing complexity, time, cost, and energy expenditure that maximize production and access quality. Overall, streamlining assisted with digital and 3D print technology transforms medical biotechnology from cell manufacturing to precision and regenerative medicine.

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BIOMEDICAL APPLICATIONS

Due to its distinguishing biological, chemical, and physical properties, $Zn_xFe_{2-x}O_3$ nanoparticles are widely used in biomedical applications. Most importantly, it is used in medical biotechnology, regenerative medicine, personalized medicine, and nanomedicine. Its ability to react/interact with biological fluids, typically with red blood cells, hemoglobin (Hb), DNA, RNA, and body tissues, is the focus of this research. This research, therefore, describes the use of $Zn_xFe_{2-x}O_3$ nanoparticles for many genetic disorders, epidemic disease, and pandemic disease. By wisely assessing and identifying the symptoms, causes, detection, and diagnosis mechanisms, magnetic nanoparticles can be adapted for cell separation, diagnosis, imaging, drug delivery, and predicting patients' outcomes. In this research, some of the major proactive use of magnetic $Zn_xFe_{2-x}O_3$ nanoparticles are presented in a concise manner.

$Zn_xFe_{2-x}O_3$ nanoparticles are highly biocompatible, thermally stable, and controlled by an optimum magnetic field. Besides, the ferrofluid and nanofluidic characteristics of $Zn_xFe_{2-x}O_3$ nanostructure are investigated for application in bioelectronics or telemedicine, anticancer, antibiotic, antimicrobial, and regenerative medicine. Magnetic nanoparticles, including $Zn_xFe_{2-x}O_3$ nanoparticles, are valuable in gene and DNA sequencing technologies, as well as DNA purifications, DNA extractions, and next-generation sequencing. As Tang C, et al. (2020) [48] noted, magnetic nanoparticles are also used as a microfluidic platform such as lab-on-a-chip (LOC) and biomarker in complex clinical samples. Zhu S, et al. (2015) [49] also revealed that the biocompatibility of Zn-doped iron oxide nanoparticles can be evaluated through a multi-tiered approach that includes in vitro and in vivo testing to assess cytotoxicity, oxidative stress, immune response, and biodistribution. To ensure the biomedical applications, it is also important to test the PH value of nanoparticles. Moreover, it is also important to modify its crystal structures, band gaps, and magnetic states of $Zn_xFe_{2-x}O_3$ by controlled doping with Zn. Then, analyzing its interaction with body fluids – such as blood – is necessary.

Tailoring these properties enables tuning the magnetic $Zn_xFe_{2-x}O_3$ nanoparticles treatment of gynecologic and oncologic diseases, typically cancers. There are several methods to treat this disease, including Physiotherapy, chemotherapy, flash radiotherapy, and immunotherapy. However, due to risk factors associated with fluid contamination, physical injuries, and recovery time, during such therapeutic techniques, mostly chemotherapy, these methods encounter a few limitations. In this circumstance, the use of magnetic nanoparticles – such as $Zn_xFe_{2-x}O_3$ – is promising due to its ability to combine both diagnosis and therapy, theranostics methods. These nanoparticles are used in all dimensions, such as sensing, therapeutic activity, diagnosis, imaging, drug delivery, and as a treatment agent.

Most importantly, it is used in cancer treatment, cell repair, tissue repair, and wound dressing/healing. By identifying the symptoms for a variety of cancers, for example, brain cancers, breast cancers, cervical cancer, they can be controlled and treated by optimizing magnetic nanoparticles. The symptoms of brain cancers, for example, are headache, Nausea, numbness, seizures, and hypertension due to abnormal tumor growth. Superparamagnetic iron oxide nanoparticles are primarily researched for cardiac/cardiovascular diseases for preventing strokes, preventing blood clots, regulating heart rhythm, and generating heart tissue after heart attacks.

Mostly, cancer is caused by gene and protein alteration in the chromosomes, damage in DNA and RNA, ionizing radiation, retrovirus, alcoholic drinks, and sometimes heredity. Particularly, damage in DNA, RNA and genes is an ideal marker for detecting point mutations in the sRNA, mRNA, and DNA. Ionizing radiation can lead to somatic and genetic damage in biological systems, including non-cellular reproductive cells. At high doses, such damage can lead to cancer or seriously alter the characteristics of specific organisms. Thus, by tailoring these symptoms, causative agents, and transmission pathways, cancers, including brain, breast, cardiac, cervical, etc., can be treated by magnetic $Zn_xFe_{2-x}O_3$ nanoparticles.

$Zn_xFe_{2-x}O_3$ nanoparticles conjugated with aptamers are active in detecting and diagnosing DNA damage. Aptamers, as artificial DNA, RNA, or peptide chains, bind a specific target molecule. Moreover,

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the ability of magnetic nanoparticles to interact with human body fluids, such as Hemoglobin, DNA, and genes, makes it promising for cell therapy, gene therapy, immunotherapy, and for advanced treatment of infection disease such as influenza, COVID-19, Tuberculosis (TB), Malaria, and HIV/AIDS. As Stueber DD. (2021) [50] published, "lab-on-a-chip" technology benefits from the increased control of magnetic nanoparticles that enable improved cellular separation. Moreover, effective use of $Zn_xFe_{2-x}O_3$-based nanomedicine helps to reduce risk effects associated with blood contamination and viral disease, such as HPV, responsible for various cancers, including brain, breast, lung, and cervical cancers. Not only used for the treatment of infectious diseases but also used for the treatment of many other diseases, particularly heart cancers, hyperthemia, thalassemia, diabetes, anemia, and Alzheimer's disease.

Magnetic nanoparticles, specifically superparamagnetic iron oxide nanoparticle personalized medicine and forensics to improve the speed and efficiency of DNA profiling techniques. $Zn_xFe_{2-x}O_3$ nanoparticles have a principal role in the advancements of medical biotechnology. They are quite important nanomaterials for magnetic resonance imaging, cell separation, cell growth, cell detection, tissue regeneration & repair, and hence for regenerative medicine. As Tseriotis VS, et al. (2025) [51] revealed, magnetic $Zn_xFe_{2-x}O_3$ nanoparticles can serve as a therapeutic agent for neurodegenerative diseases, diabetes, and even next-generation gene sequencing. Magnetic nanoparticles are inherently used for the diagnosis, prevention, and treatment of infectious diseases. Most importantly, they are used for the treatment of hereditary, mental, and hematologic diseases, and orthopedic diseases, including anemia, Alzheimer's disease, diabetes, multiple sclerosis (MS), thalassemia, and osteoporosis by improving bone density.

$Zn_xFe_{2-x}O_3$ nanoparticles can be used to influence cell signaling, regulating gene expression, gene circuit, and gene sequencing. As Hadjikhani A, et al. (2017) [52] demonstrated, magnetoelectric nanoparticles (MENs) provide unique properties making them ideally suitable for the emerging fields of precision medicine and nanomedicine, particularly for cancer and neurodegenerative diseases. It has a significant role in the research and development of regenerative medicine, Medical Biotechnology, and personalized medicine. Modeling $Zn_xFe_{2-x}O_3$ nanoparticles facilitates the healing of skin wounds and bone regeneration. and tissue repair.

In general, although magnetic nanoparticles – such as $Zn_xFe_{2-x}O_3$ – are extremely important medical materials, the extent of utilization is limited to the regulatory rules of the World Health Organization (WHO). Accordingly, the WHO recommended safe handling of manufactured nanomaterials (MNM), assessing health hazards of MNMs, assessing exposure to MNMs, and controlling exposure to MNMs. It is again recommended that the fabrication and utilization of medical materials should be defined in consideration of validated measurement techniques and risk assessment factors.

In the future, we are fortunate of synthesizing magnetic nanoparticles, such as $Zn_xFe_{2-x}O_3$, using ferrocene by combining zinc precursors with ferrocene, followed by oxidation or heat-treatment. This can be confirmed by careful observation via the microscopic process of interaction between magnetic nanoparticles and ferrocene-bearing organic molecules such as dendrimers. Magnetic nanoparticles prepared in this way have high stability and are used for anticancer activity, in drug delivery, and as a therapeutic agent.

CONCLUSION

In this research, the design, model, synthesis, characterization methods, and potential role of magnetic $Zn_xFe_{2-x}O_3$ nanoparticles are noted. The biophysical properties, including biocompatibility, bioavailability, thermal stability, and interaction with DNA and Hb, are envisioned. Moreover, the ability of magnetic nanoparticles to interact with human body fluids, such as Hemoglobin, DNA, and genes, makes it promising for various therapeutics, advanced infectious control, and treatment. Besides, their potential application in biomedicine, particularly in medical biotechnology, is studied in detail. To spec-

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ify their functional properties, the role of nanotechnology is accounted. More specifically, the significance of nanotechnology in synthesizing, manipulating, characterizing, and utilizing $Zn_xFe_{2-x}O_3$ nanoparticles is seen. Experimentally, magnetic nanoparticles can be synthesized by a variety of methods. However, this research has given greater emphasis to the Solvothermal method and biological (green) synthesis methods. Accordingly, the solvothermal method is seen as an effective magnetic nanoparticle synthesis method while enabling high crystal quality, uniformity, and high yield, but with low cost. On the other hand, biological or green synthesis of $Zn_xFe_{2-x}O_3$ nanoparticles is highly promising since it is cost-effective, eco-friendly, and contribute for sustainability motion. Moreover, strategies are proposed to accelerate performance, maximize production, and improve access quality in precision medicine and medical biotechnology.

Moreover, effective use of $Zn_xFe_{2-x}O_3$-based nanomedicine helps to reduce risk effects associated with blood contamination and viral diseases, such as HPV, responsible for various cancers, including brain, breast, cervical cancers, and lung cancer. Magnetic nanoparticles are not only used to treat infectious diseases but also used for the treatment of many other diseases, particularly anemia, Alzheimer's disease, diabetes, multiple sclerosis (MS), thalassemia, and osteoporosis by improving bone density.

When properly designed, modeled, and tailored, magnetic $Zn_xFe_{2-x}O_3$ nanoparticles can reduce health risk effects associated with chemotherapy, radiation therapy, and radiotherapy. Moreover, they can improve detection and monitoring systems, typically biomarkers and nanosensors, which are useful in controlling, detecting, sensing, and bio-labeling infectious and cardiovascular diseases. $Zn_xFe_{2-x}O_3$ nanoparticles-based nanobiosensor helps to sense, monitor, and serve as both cancer biomarkers and treatment. They improve the performance of biomarkers and nanobiosensors, enabling to detect and diagnosis infections disease, serve as a therapeutic agent, and enable to predict patient's treatment outcomes. Ultimately, the proper use of magnetic nanoparticles fosters medical biotechnology and regenerative medicine. Although the use of magnetic nanoparticles is efficient and reliable in medical treatment, it is important to be aware of policies, regulatory rules, and ethics concerning the dose, injection methods, and safety.

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Conflict of Interest

The research declares that there is no conflict of interest due to a variety of resources, financial issues, and ethical issues.

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