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Review

A review on antimicrobial properties of nano-ferrites: Biomedical applications

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Abstract: This review focuses on ferrites, which are gaining popularity with their unique properties like high electrical resistivity, thermal stability, and chemical stability, making them suitable for versatile applications both in industry and in biomedicine. This review is highly indicative of the importance of synthesis technique in order to control ferrite properties and, consequently, their specific applications. While synthesizing the materials with consideration of certain properties that help in certain methods of preparation using polyol route, green synthesis, sol-gel combustion, or other wise to tailor make certain properties shown by ferrites, this study also covers biomedical applications of ferrites, including magnetic resonance imaging (MRI), drug delivery systems, cancer hyperthermia therapy, and antimicrobial agents. This was able to inhibit the growth of all tested Gram-negative and positive bacteria as compared with pure ferrite nanoparticles without Co, Mn or Zn doping. In addition, ferrites possess the ability to be used in environmental remediation; such as treatment of wastewater which makes them useful for high-surface-area and adsorption capacity due heavy metals and organic pollutants. A critical analysis of functionalization strategies and possible applications are presented in this work to emphasize the capability of nanoferrites as an aid for the advancement both biomedical technology and environmental sustainability due to their versatile properties combined with a simple, cost effective synthetic methodology.

Keywords: nano-ferrites; ferrites; dopants; biomedical

1. Introduction

Human development is the epicenter of all study through the use of resources and the creation of new chemicals that benefit society. In particular, magnetic materials have grown in significance, and now, these are widely employed in many different sectors because of their unique properties; these properties are used in many fields, such as the chemical industry, the medical field, and electronics [1]. When pure metals are compared with ferrite materials, which are known as magnetic materials due to their special properties, this includes low cost, high resistance, and simple production processes. In ferrites, ferric oxides are the main components, which are a mixture of other metal oxides; these ferrites can be synthesized by using hematite (Fe_2O_3) or magnetite (Fe_3O_4) and are typically non-conducting [2].

The characteristics of structural, electrical and magnetic are greatly improved by substituting tiny quantities of dopants, which makes ferrites appropriate for many technological applications [3]. The production of nanoferrites has received great interest which is due to their improved magnetic and electrical characteristics and this is easy comparable bulk counterparts [4,5]. These ferrites useful for different field due their improved magnetic characteristics which is in nanoscale in size, and also contain lager surface to volume ratio and quantum confinement effect [6]. This result indicates that nanoferrites is a essential materials for industry and technology, propelling breakthroughs in electronics, telecommunications, and healthcare. High magnetic permeability, chemical and thermal stability, high electrical resistivity, and gentle magnetic behavior are just a few of the remarkable qualities that ferrites have. These characteristics make them extremely adaptable for a different application, which includes choke coils, Ferrites are utilized across a range of applications due to their unique properties. In microwave frequency devices, they exhibit high permeability (μ > 1000) and low loss tangents (tan δ < 0.1), facilitating efficient signal transmission. In computer memory core elements, magnetic saturation (50–80 emu/g) and moderate coercivity (Hc~20–300 Oe) ensure reliable data storage and retrieval. For biomedical applications, surface-coated ferrites (PEG or silica) with particle sizes of 10–100 nm enhance biocompatibility and cellular uptake. They also show promise in hyperthermia treatments with a specific absorption rate (> 100 W/g) and smaller particle sizes (10–50 nm) for effective heat generation. In drug delivery, ferrites allow for targeted therapy through magnetic saturation (50–80 emu/g) while maintaining biocompatibility. Their antibacterial and antifungal efficacy is supported by small particle sizes (10–50 nm) and functionalization with antimicrobial agents, ensuring chemical stability across various pH ranges. Lastly, in water treatment, nano-sized ferrites (10–200 nm) with magnetic saturation (50–70 emu/g) and a surface area of 50–150 m^2/g enable efficient, transformer cores, antenna rods, gas sensors, recording heads, electrodes telecommunication systems, and biomedical applications like drug delivery, magnetic hyperthermia, and magnetic resonance imaging [7–9]. The electrical and magnetic characteristics work together to provide substantial performance and efficiency gains, making them widely used in contemporary electronics and healthcare systems [10–12].

This review article starts a discussion of different synthesis methods for ferrites, their antibacterial characteristics, and their prospective uses in biomedicine. In specific condition the dopants to the improvement of their characteristics are discussed, along with the difficulties and prospects associated with the switch from bulk to nano-ferrites for next-generation technological advancements.

2. Synthesis of ferrites

The synthesis methods of ferrites are critically important because the properties and applications of ferrites are highly dependent on their synthesis techniques. The choice of synthesis method influences the size, shape, purity, crystallinity, magnetic properties, and surface characteristics of the ferrite nano-particles. These factors, in turn, determine the material's suitability for specific applications, such as in electronics, catalysis, medical devices, and environmental remediation. Many synthesis techniques is shown in **Figure 1** like Ball milling, Solid state reaction method, Coprecipitation method, Hydrothermal, Micro-emulsion techniques are used to synthesize ferrite materials [13–16]. Different approaches like Polyol technique, Green Synthesis technique, Sol gel method, Sol gel auto-combustion Fast firing method (Pramanik Method) etc., are employed to prepare ferrites [15–23].

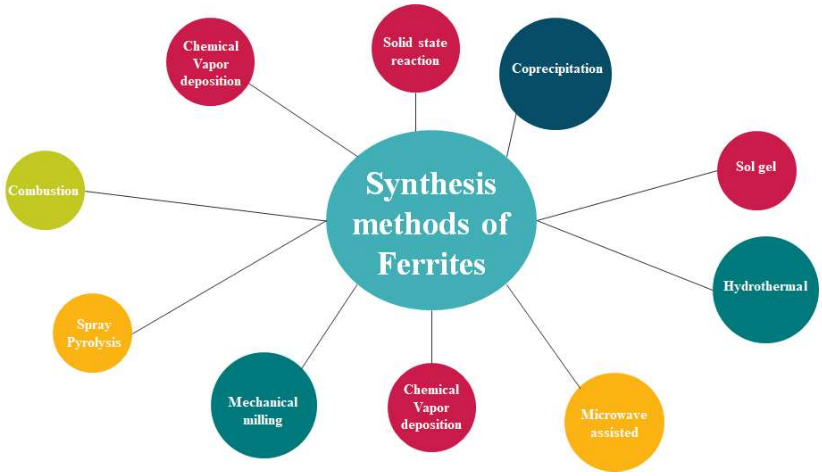

Figure 1. Synthesis techniques of ferrites.

Table 1. Different synthesis methods of ferrites.

Method	Description	Key Features	Typical Conditions
Solid-State Reaction	Mixing metal oxides or carbonates followed by high-temperature sintering.	Simple, cost-effective, suitable for bulk synthesis	High temperatures (1000–1400 °C), long sintering times (4–8 h)
Sol-Gel Method	Using metal alkoxides or nitrates to form a gel, followed by drying and calcination.	High purity, fine particle size, homogeneity	Low to moderate temperatures (400–800 °C), controlled atmosphere
Co-precipitation	Precipitating metal hydroxides from a solution, followed by drying and calcination.	Uniform particle size, suitable for nanoparticles	Moderate temperatures (300–700 °C), pH control during precipitation
Hydrothermal Synthesis	Reacting metal precursors in a sealed vessel at high pressure and temperature.	Controlled particle size, high crystallinity	High pressures (autoclave), moderate to high temperatures (150–300 °C)
Microwave-Assisted Synthesis	Using microwave radiation to heat precursors rapidly, leading to faster reaction times.	Fast processing, energy efficient, fine particles	Rapid heating, moderate to high temperatures (100–200 °C)
Mechanical Milling	Ball milling metal oxides or carbonates to achieve fine particle sizes before sintering.	Simple, scalable, cost-effective	Room temperature for milling, high temperatures for sintering
Spray Pyrolysis	Spraying a solution of metal salts into a hot furnace to form fine particles through pyrolysis.	Fine, spherical particles, continuous process	High temperatures (800–1200 °C), controlled spray conditions
Combustion Synthesis	Using a fuel and oxidizer mixture to ignite a self-sustaining combustion reaction.	Rapid, energy efficient, can produce high-purity products	Exothermic reaction, moderate temperatures (300–600 °C)
Chemical Vapor Deposition (CVD)	Decomposing metal precursors in vapor phase onto a substrate to form ferrites.	High purity, controlled composition, and thickness	High temperatures (500–1000 °C), vacuum or controlled atmosphere
Electrochemical Deposition	Electroplating metal ions onto a substrate to form ferrite films.	Precise thickness control, suitable for thin films	Room to moderate temperatures (25–100 °C), controlled current/voltage

Table 1 depicts different synthesis methods, description of techniques, key features of synthesis methods and requirement of typical conditions for synthesis of ferrites [17,24]. The synthesis of ferrites is critically important because it dictates the material's final properties, and including yield which can improve by optimizing key factors such as temperature, reaction time, pH level, precursor concentration, and stirring speed. Considering choice of the solvent and fuel to oxidant ratio in methods like sol-gel or auto-combustion plays a significant role, controlling reaction cooling

rates enhance product quality and yield, sometime crucial for their performance in various applications. By choosing and optimizing the synthesis method, researchers and engineers can tailor ferrites for specific uses, ensuring they meet the necessary requirements in fields ranging from electronics to medicine.

3. Biomedical applications of ferrites

Nanoferrites have obtained a significant attention due to their applications in different fields ranging from industry to biomedicine (**Figure 2**) [25]. One of the applications is magnetic resonance imaging (MRI), the most common use of nanoferrites in biomedicine field as a contrast agent. This MRI is a non- invasive diagnostic technique that helps to get detailed picture of the body tissues. MRI modifying the relaxation duration (T_1 and T_2) by adjacent water protons, iron oxides like magnetite helps find the difference between normal and diseased tissue by making the tissues harboring these nanoparticles seem brighter or darker in the MRI images. Similarly, manganese ferrite ($MnFe_2O_4$) and cobalt ferrite ($CoFe_2O_4$) used to get sharper, higher-resolution pictures [23–29]. The magnetic hyperthermia is a method where nanoferrites also used to treat cancer, magnetic nanoparticles are subjected to an alternating magnetic field, this technique utilized the particle’s temperature. This heated particle injected in to the diseased tissues causes the tumor cells to heat up to a point where all cancer cells die, but leaving the surrounding healthy tissues unaffected [30–33]. Cobalt ferrites is a an important to treat the magnetic hypothermia-based cancer treatment using Cobalt ferrites which is a magnetic hyperthermia-based cancer therapy because of their high coercivity and magnetic saturation [34–36]. For magnetic refrigeration, key parameters include high magnetic anisotropy (K: 104 to 106 J/m^3), significant adiabatic temperature change (ΔTad: 2–4 K at 2–5 Tesla), and a transition temperature near room temperature (Tc: 290–310K). Common materials include gadolinium (Gd), with a transition temperature of 293 K and ΔT_{ad} of~3–4 K, and Gd-alloys like Gd-Si-Ge, which enhance refrigeration properties [37]. The main reason to study for the targeted drug delivery methods represents a notable’s applications in biomedicine. Delivering medicines to targeted locations like tumor or particular organ these systems are intended to increase the effectiveness of medicine while lowering the amount of the drug that comes into contact with heathy tissues, to avoid adverse effects. The infected cells or organ medication is delivered in a regulated manner once it reaches the target, guaranteeing minimum systemic toxicity and high therapeutic concentrations at the illness site. Once the targeted organ treated very well need to make sure the health of the cells needs to monitor with the help of biosensors which is based on nano-ferrites which is also became very essential tool in diagnostics and healthcare. These biosensors designed to detect biological entities such as proteins, DNA, or pathogens. The combination of nano-ferrites with bio-molecules that bind to specific target analytes, these particles can provide highly sensitive detection of disease markers, toxins, or infectious agents. For example: Cobalt ferrite ($CoFe_2O_4$) and zinc ferrite ($ZnFe_2O_4$) ferrites used in biosensors due to their stability and large surface area, which improves ability of sensors and also its very important to detect early diagnosis, enabling more timely treatment and patient outcomes [36,37]. The nanoferrites can also exabits strong antimicrobial properties that makes suitable for many applications in health care segment where infection control is critical, some nanoferrites, particularly those doped with other metals like zinc, copper and silver are known as disrupt the cell membranes of bacteria and fungi, leading to their destruction. This quality used in antimicrobial ferrites can be incorporated into medical device coatings, wound dressings, or even hospital textiles, where they act as barriers to microbial growth. This kind of feature is very important to prevent hospital acquired infections, which are major cause of complications and healthcare system [38–48]. In addition to this nano-ferrites are being explored for different use in this section medical field being explored for use in tissue engineering and regenerative medicine. When combined with biodegradable scaffolds, magnetic nanoparticles can be used to guide cell growth and tissue regranulation scaffolds, magnetic nanoparticles can be used to guide cell growth and tissue regeneration through the application of magnetic fields. This approach has been particularly promising in regeneration of bones and nerves, where magnetic fields can help to align bio cells in a way that mimics tissue natural growth, accelerating the healing process. Ferrites, NdFeB magnets, and Samarium Cobalt (SmCo) magnets exhibit distinct magnetic properties, making them suitable for various applications. Ferrites typically have a coercivity (H_c) ranging from 400 to 450 kA/m, a Curie temperature (Tc) between 300 and 450 °C, and an energy product (B_{Hmax}) of 1 to 5 MGOe (8 to 40 kJ/m^3). In contrast, NdFeB magnets possess higher coercivity values, ranging from 800 to 2000 kA/m, with a Curie temperature of 310 to 400°C (which can be elevated with doping), and an impressive energy product of 30 to 55 MGOe (240 to 440 kJ/m^3). Samarium Cobalt magnets also demonstrate significant coercivity, ranging from 600 to 2000 kA/m, with a higher Curie temperature of 720 to 820 °C and an energy product between 16 to 30 MGOe (128 to 240 kJ/m^3) [23,49–54].

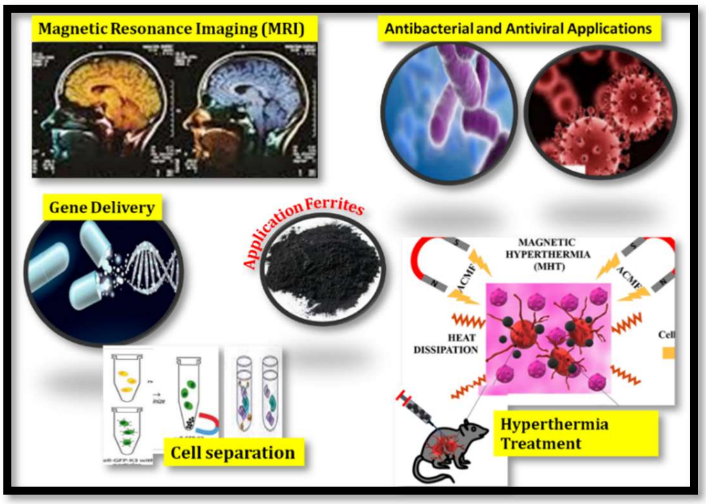

Figure 2. Schematic diagram of biological applications of ferrites.

3.1. Diagnosis and MRI imaging

Medical imaging being used an important tool by using ferrite nanoparticles which is very actively and effective in diagnosing cancer. Actually, these nanoparticles are very useful and have protentional to high to provide high quality interior picture of human body. Magnetic Resonance Imaging (MRI) is the most widely used therapeutic instruments [55,57]. diagnosing cancer or ill cell is not only that much important but finding exact locations, dimensions and distinction from healthy tissues. Nano ferrites such as $CoFe_2O_4$ and $FeGa_2O_4$ also one of the best examples for diagnostic applications because of their advantageous qualities, such as magnetic features that make them appropriate for improving contrast in MRI scans. $Fe_3O_4$and γ-Fe_2O_3Iron oxides nano-particles is studied for long time and being used as contrasting agents, beyond these improved imaging capabilities, manganese and Zinc doped zinc ferrite nano-particles, as well as Mn–$ZnFe_2O_4$ are also emerging as viable possibilities [41,50].

$MnFe_2O_4$ ferrites are the nano particles are new MRI contrast agents that provide better performance than conventional ferrites like Fe_3O_4, γ-Fe_2O_3, $CoFe_2O_4$, and $NiFe_2O_4$ best for magnetic characteristics including their reduced toxicity and biocompatibility. Using $MnFe_2O_4$ nano-particles in MRI and developing new ferrites nanoparticles to open new possibilities for better early diagnosis and management of a range of illnesses [35,41].

3.2. Hyperthermia

Magnetic hyperthermia is important and cutting-edge technical tool to cure cancer, in this method heat applies to tumor location in order to kill cancerous cells. The process of heating at exact location is possible by only using ferrite-based nanoparticles have a special capacity to absorb energy when exposed to an external alternating magnetic field [32,34,35]. The successful elimination of malignant cells while protecting healthy ones, a condition known as hyperthermia [54,55]. This treatment technique is very sensitive technique to eliminate malignancy at exact location resulting in classifications of localized, regional, whole-body hyperthermia [54]. Timer cells are intrinsically more heat-sensitive than normal cells because of their atypical blood arteries, these arteries works differently so this is very week and more sensitive towards heat. The Fe_3O_4 applied for tumor treatment are proficiently studied, these nanoparticles uses Néel and Brownian relaxation to collect energy from the magnetic field and transform it into heat [55]. $CoFe_2O_4$nanoferrite has immense capacity of self-heating and therefore is the most encouraging nanoferrite for application of hyperthermia [57]. These nanoparticles magnetic nature, size and shape of a particle, including intensity and frequency of the applied magnetic field, all these depends on how much heat they produce. The Fe_2O_4 nanoferrite or Co $Fe_3O_4$are able to absorbing magnetic energy and releasing it as heat (42–45 °C) due to this is used in hyperthermia treatments. This type of treatment helps to kill directly or make very week towards the treatment like radiation and chemotherapy. This technological development provides focused, non-invasive approach to cancer treatment which has great protentional to improve the efficacy of currently available medicines and lessons the adverse effects of old traditional approaches.

3.3. Drug delivery and release

Ferrite nanoparticles show significant advantages such as treating cancer, delivery of drug and its release and safe excretion from the human body. For instance, the test carried on synthesized $CoFe_2O_4$ nanoparticles disclosed all the above-mentioned benefits [58]. In comparison with conventional drug use, the utilization of nanoferrites has helped to minimize the requirement of drug needed and related side effects [59,60]. In treating cancer by this system, the nanoferrites act as core whereas various biocompatible organic moieties act as shell. Ferrite nanoparticles are capable of carrying drugs and circulating them without dripping. They also effortlessly travelto the site of target tumor with the help of an external magnetic field. They support in lending effective treatment by bypassing normal cells [61]. After delivering the drugs, either they get removed from the human body or get biodegradable [62]. The method of targeted drug delivery is having variousbenefit's like depletion of wastage of drug, minimizing the drug administration frequency, lowering side-effects, increasing efficacy of treatment, being safe and reliable [32] etc. manganese (II) complexes is a high catalytic activity which has a potential benefit in medical applications, for drug synthesis or therapeutic applications which is helpful medication manufacturing and treatment procedures [63]. Zirconium oxide (ZrO_2) synthesized material which has high optical characteristics and cubic structure with size of the grain ZrO_2 is 10–30 nm due to this which suitable to get improved by surfactants like polyethylene glycol (PEG) have great potential which is used for drug delivery [64]. Copper (II) hexaaza macrocyclic complexes is new content which is synthesized by using situ one-pot template synthesis (IOPTS) ultimately a good for drug delivery [65]. Ferrites are valuable in various applications, including drug delivery, antibacterial/antifungal treatments, and water treatment, due to their unique properties. For drug delivery, key parameters such as particle size (10–100 nm), magnetic saturation (50–80 emu/g), biocompatibility (surface-coated with PEG, silica, dextran), and zeta potential (−30 to +30 mV) enhance cellular uptake and ensure effective targeting and stability. In antibacterial and antifungal applications, small particle size (10–50 nm), appropriate magnetic saturation (40–70 emu/g), surface functionalization with antimicrobial agents, and chemical stability in various environments are crucial for maximizing antimicrobial efficacy. For water treatment, ferrites should exhibit a particle size of 10–200 nm, magnetic saturation of 50–70 emu/g, high chemical stability across pH ranges, and a large surface area (50–150 m^2/g) to optimize pollutant removal and ensure durability in treatment processes [54,66–68].

3.4. Antibacterial and antifungal studies

Nano ferrites exhibit antibacterial and antifungal properties due to several key factors related to their unique chemical composition, surface characteristics, and magnetic properties. Nano ferrites possess a high surface-to-volume ratio, which increases the interaction between the nanoparticles and microbial cells. This enhanced contact can lead to more efficient microbial killing. The surface of nano ferrites can generate reactive oxygen species (ROS) when exposed to environmental conditions. ROS, such as hydroxyl radicals, superoxide anions, and hydrogen peroxide, can damage microbial cell membranes, proteins, and DNA, leading to cell death. Magnetic nanoparticles are significantly used as antibacterial and antifungals. The preparation and verification are done for nanoferrites for their extensive usage in medicinal field [69,70]. As antifungals are toxic, less efficient and resistant, there is a need for developing novel antifungal drugs that are safe and efficient. Therefore, taking into account these aspects, new antifungal substances have evolved [71]. Cobalt ferrite nanoparticles have been shown to exhibit significant antibacterial activity. The mechanism involves the generation of ROS and the release of cobalt ions, which can penetrate bacterial cells and cause oxidative damage. Zinc ferrite nanoparticles are known for their antifungal activity. Zinc ions can interfere with fungal cell wall synthesis and membrane integrity, while the ferrite structure helps in the generation of ROS, leading to fungal cell death. Thus Nano ferrites show antibacterial and antifungal properties due to their high surface area, magnetic properties, metal ion release, and ability to generate reactive oxygen species. These properties make them effective in disrupting microbial cells and killing bacteria and fungi.

The Kirby–Bauer also called agar diffusion test is an antibiotic susceptibility test that makes use of discs of antibiotics to examine the extent of bacteria and fungi [72]. Zinc Copper ferrites were studied for antibacterial activity where it was noticed that activity was dependent of zinc concentration [53]. The Zinc substituted Cobalt ferrite and Manganese substituted Cobalt ferrite were utilized for antibacterial and antibiofilm activities towards bacteria that commonly diffused on the surfaces of medical operating room walls [73]. The Mg substituted Mn-Zn ferrites act as outstanding antimicrobial potentials [42].

Also, the cobalt doped manganese ferrites are proposed as a candidate material for industries manufacturing antifungal products [74]. Ag doped Ni Co nanoferrites show an exceptional antifungal action [75]. **Figure 3** is a schematic representation of biological applications of ferrites whereas **Table 2** provides information about different biological applications of ferrites along with the description. Thenanoferrite sample $Ni_{0.45}Zn_{0.45}$Cu0.1Fe_2O_4 exhibited the highest antibacterial activity against Bacillus cereus, with inhibition zones measuring 21, 23, 23, and 23 mm for concentrations of 25, 50, 100, and 250 µg/ml, respectively (**Table 3**). **Figure 4** and **Figure 5** illustrate the antibacterial studies of nickel zinc ferrites and copper-doped nickel zinc ferrites. In contrast, the other nanoferrite samples demonstrated negligible antibacterial activity. The antifungal activity was evaluated for cobalt-doped nickel zinc ferrites, with $Ni_{0.45}Zn_{0.35}Co_{0.2}Fe_2O_4$ showing the highest inhibition zones of 25, 27, 30, and 30 mm for 25, 50, 100, and 250 µg/ml concentrations against Aspergillus niger (**Table 4**) [56]. **Figures 6** and **7** present the antifungal studies of nickel zinc ferrites and cobalt-doped nickel zinc ferrites. The results highlight the importance of compositional variations in enhancing the antimicrobial properties of nanoferrites, paving the way for their potential use in biomedical applications.

Table 2. Biological applications of ferrites with description.

Biological application	Description	Reference
MRI Contrast Agents	Ferrite nanoparticles enhance MRI contrast by affecting the relaxation times of hydrogen nuclei in tissues.	71
Drug Delivery	Magnetic ferrite nanoparticles can be directed to specific locations in the body using an external magnetic field, allowing for controlled drug release.	72
Hyperthermia Treatment	Magnetic ferrite nanoparticles generate heat when exposed to an alternating magnetic field, which can be used to kill cancer cells selectively.	73
Biosensors	Ferrite nanoparticles enhance the sensitivity and specificity of biosensors used to detect various biological molecules.	38
Cell Separation	Cells can be tagged with magnetic ferrite nanoparticles and separated from a mixture using a magnetic field.	74
Antifungal Applications	Ferrite nanoparticles exhibit antifungal properties, inhibiting the growth of various fungal species.	42
Antimicrobial Applications	Ferrite nanoparticles have antimicrobial properties effective against a wide range of bacterial strains.	43
Antibacterial Coatings	Ferrite nanoparticles can be used in coatings to prevent bacterial colonization on medical devices.	44
Antimicrobial Textiles	Ferrite nanoparticles are incorporated into textiles to provide long-lasting antimicrobial properties.	45
Water Purification	Ferrite nanoparticles can be used to remove microbial contaminants from water, providing an effective purification method.	46

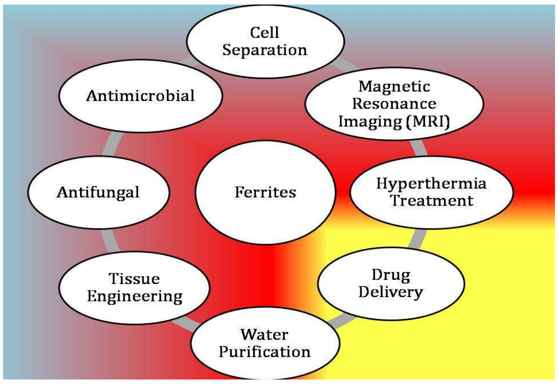

Figure 3. Schematic diagram of biological applications of ferrites.

Table 3. Antibacterial activity of copper doped nickel zinc nano ferrites against bacillus cerus.

Sample	Zone of inhibition(mm)			
	25µg/mL	50µg/mL	100 µg/mL	250 µg/mL
$Ni_{0.45}Zn_{0.55}Fe_2O_4$	1	1	2	1
$Ni_{0.45}Zn_{0.45}Cu_{0.1}Fe_2O_4$	21	23	23	23
$Ni_{0.45}Zn_{0.35}Cu_{0.2}Fe_2O_4$	1	1	2	1
$Ni_{0.45}Zn_{0.25}Cu_{0.3}Fe_2O_4$	1	1	2	1

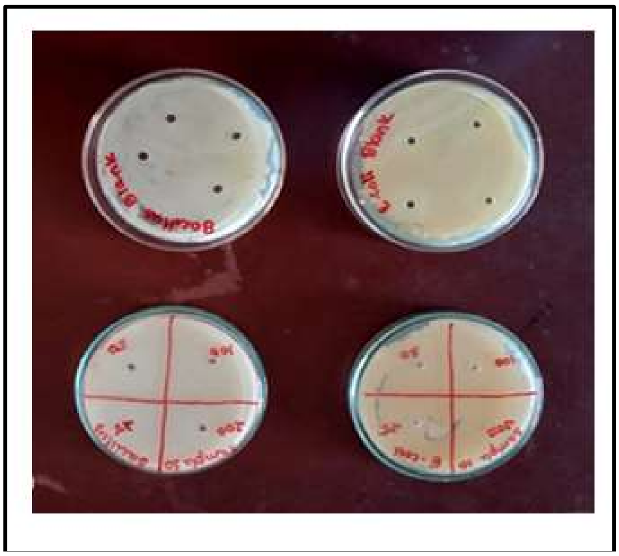

Figure 4. Antibacterial activity of nickel zinc nanoferrites ($Ni_{0.45}Zn_{0.55}Fe_2O_4$) against bacilluscerus.

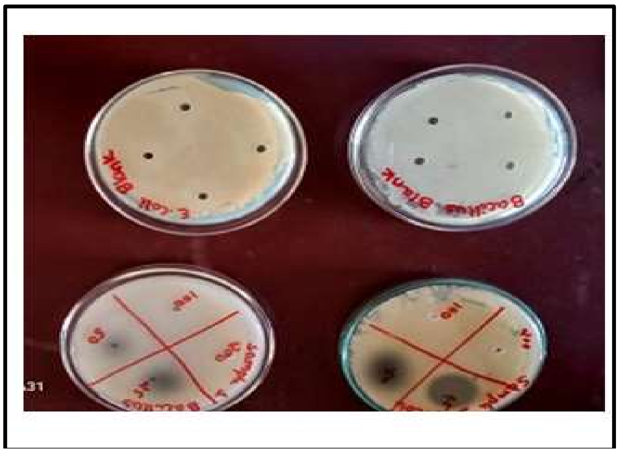

Figure 5. Antibacterial activity of copper doped nickel zinc nanoferrites ($Ni_{0.45}$ $Zn_{0.45}Cu_{0.1}Fe_2O_4$)againstbacillus cerus.

Table 4. Antifungal activity of cobalt doped nickel zinc nanoferrites against Aspergillus niger.

Sample	**Zone of inhibition(mm)**			
	25μg/mL	**50μg/mL**	**100 μg/mL**	**250 μg/mL**
$Ni_{0.45}$ $Zn_{0.55}Fe_2O_4$	1	2	2	1
$Ni_{0.45}$ $Zn_{0.45}Co_{0.1}Fe_2O_4$	1	2	2	1
$Ni_{0.45}$ $Zn_{0.35}Co_{0.2}Fe_2O_4$	25	27	30	30
$Ni_{0.45}$ $Zn_{0.25}Co_{0.3}Fe_2O_4$	1	2	2	2

Figure 6. Antifungal activity of nickel zinc nanoferrites ($Ni_{0.45}$ $Zn_{0.55}Fe_2O_4$) against Aspergillus niger.

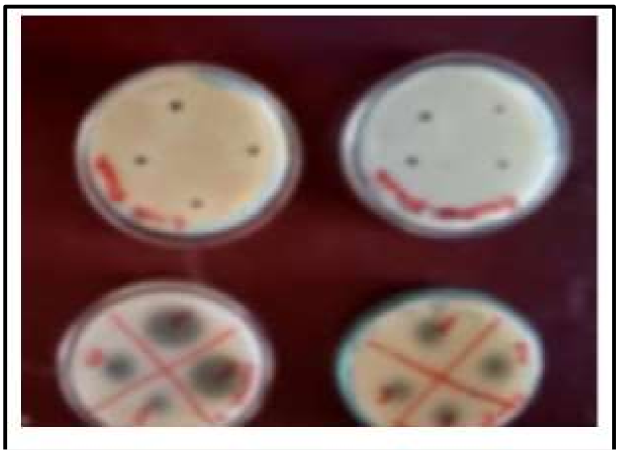

Figure 7. Antifungal activity of cobalt doped nickel zinc nanoferrites ($Ni_{0.45}$ $Zn_{0.35}Co_{0.2}Fe_2O_4$) against Aspergillus niger.

Thus unique magnetic properties and biocompatibility of ferrites (**Table 5)** make them invaluable in various biological and medical applications, shown in **Figure 8**. Research continues to expand their potential uses, offering promising advancements in diagnostics, treatment, and research methodologies in the life sciences. Ferrites exhibit notable antibacterial and antifungal properties, with particle sizes typically ranging from 10–50 nm for Fe_3O_4 (magnetite), effective against E. coli and S. aureus, and 20–60 nm for $CoFe_2O_4$ (cobalt ferrite), demonstrating antibacterial activity against E. coli. Their magnetic saturation (Ms) values are 40–60 emu/g for magnetite, enhancing drug targeting, and 25–35 emu/g for $ZnFe_2O_4$ (zinc ferrite), which still shows moderate antibacterial activity. Zeta potential for magnetite ranges from −10 to −20 mV, ensuring stability in colloidal suspension. Minimum inhibitory concentrations (MIC) for Fe_3O_4 nanoparticles are 50–100 µg/mL for E. coli and S. aureus. $CoFe_2O_4$ achieves 80%–90% antibacterial efficiency against E. coli, while $NiFe_2O_4$ (nickel ferrite) shows 70%–85% antifungal efficiency against C. albicans. Functionalizing ferrites, such as with silver, further enhances antibacterial activity. Ferrites are biocompatible, with cytotoxicity showing ≥80% cell viability at ≤100 µg/mL [68,76–80].

Table 5. Applications, key parameters, and their importance.

Application	Important Parameters	Reasons for Importance
Microwave Frequency Devices	Permeability, Loss Tangent (High (μ> 1000, Low (tan δ < 0.1))	High permeability ensures efficient signal transmission, while low loss tangents minimize energy loss.
	Frequency Response	Affects device performance at various microwave frequencies.
Computer Memory Core Elements	Magnetic Saturation (50–80 emu/g), Coercivity(Hc~20–300 Oe) (Hc~20–300 Oe) (Hc~20–300 Oe)	High saturation magnetization allows for reliable data storage and retrieval; moderate coercivity ensures stability.
	Thermal Stability	Essential for maintaining performance under operating conditions.
Biomedical Applications	Biocompatibility, Particle Size	Biocompatibility is crucial for safety; smaller particles enhance cellular uptake and interaction with tissues.
	Particle Size10–100 nm	Enhances cellular uptake and improves interactions with biological systems.
	Surface Functionalization	Modifications improve interactions with biological systems, reducing toxicity.
Diagnosis	Magnetic Susceptibility, Surface Coating	High susceptibility enhances imaging quality; biocompatible coatings improve safety in medical applications.
	Sensitivity and Resolution	Crucial for improving diagnostic accuracy in imaging techniques.
Hyperthermia	Specific Absorption Rate Particle Size (10–50nm)	High SAR values indicate efficient heat generation, while smaller sizes improve localization in tumors.
	Magnetic Properties	Essential for effective induction heating in targeted cancer therapy.
Drug Delivery	Magnetic Saturation (Ms), Biocompatibility	Enables targeted delivery through external magnetic fields; biocompatibility ensures safety.
	Release Profile	Important for controlling drug release rates in therapeutic applications.
Antibacterial and Antifungal	Particle Size (10–50 nm) Surface Functionalization, Chemical Stability	Smaller sizes enhance interaction with microbes; functionalization improves antimicrobial efficacy.
	Efficacy in Biological Environments	Chemical stability ensures prolonged activity in diverse conditions.
Water Treatment	Particle Size (10–200 nm) Magnetic Saturation (Ms), (50–70 emu/g) Surface Area (50–150 m^2/g)	Nano-sized particles provide high surface area for adsorption; magnetic properties enable easy recovery.
	Chemical Stability	Ensures durability and effectiveness during treatment processes across various pH levels.

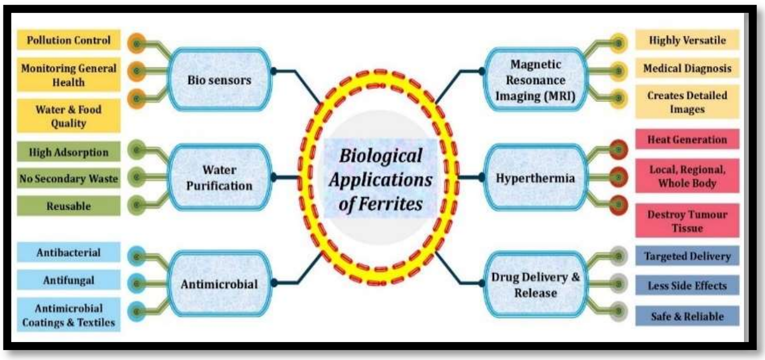

Figure 8. Various biological applications of nano ferrites.

3.5. Waste water treatment

Water sources are at high risk of pollution. They get polluted because of discharging wastes into the water bodies such as plastic, glass, chemicals, etc. The common pollutants in waste water are metal ions, aromatic compounds, anions, phenols, dyes, pesticides, detergents, etc. Because of the presence of such contaminants in waste water, it makes the water unfit for drinking and also becomes poisonous to aquatic life. Ferrites, especially those with high surface areas, are effective adsorbents for removing heavy metals like lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr^{6+}), and arsenic (As^{3+}) from wastewater due to unique properties of ferrites (**Figure 9**). The metal ions are adsorbed onto the surface of the ferrite particles through electrostatic interactions and chemical bonding. Ferrites can adsorb organic pollutants, such as dyes, from wastewater due to their surface properties and ability to be modified with functional groups that enhance adsorption. All over the world, there is demand for clean and safe water. Hence, the purification of water is of utmost priority. New methods of purification of water are to be developed that are cost effective. Magnetic nanoparticles because of their adsorption and high surface area to volume ratio have become significant candidates for treating waste water. Therefore, nanoferrites are checked for removing contaminants and purifying water. They have proved to be promising candidates in this aspect. The process of adsorption or degradation is responsible for the removal of contaminants in water [47,81–84]. The waste water of the industries is treated to remove dyes and phenols, toxic metals by using nanoferrites [75–82]. Magnetite (Fe_3O_4), Cobalt Ferrite ($CoFe_2O_4$), Nickel Ferrite ($NiFe_2O_4$), Zinc Ferrite ($ZnFe_2O_4$), Copper Ferrite ($CuFe_2O_4$), Manganese Ferrite ($MnFe_2O_4$), and Barium Ferrite ($BaFe_{12}O_{19}$)—is used in wastewater treatment for specific applications based on their magnetic properties, ability to adsorb contaminants, and catalytic capabilities. Nanoferrites are good adsorbents that are of low cost, efficient, can be recovered with ease and reused. By literature review, it is clear that trend of using nanoferrites in waste water treatment has increased. The Fe_3O_4 is a popular candidate for this. This might be because of non-toxicity, ease of availability of precursors required in its synthesis [32,85]. Dy_2O_3-SiO_2 nanocomposite is best and effective in photocatalysis which break down the pollutants like erythrosine so it's best for sanitation and environmental cleanup similarly reduced graphene oxide (RGO) from graphite oxide using urea also used as non-toxic reducing agent [70,86]. $CsPbI_3$ perovskite nanostructures is capable enough fight against the Pseudomonas aeruginosa, Escherichia coli, and Streptococcus pyogenes which is good to addressing pollution [86]. Ferrites with a large surface area (50–150 m^2/g) demonstrate high adsorption capacities, making them effective for removing heavy metals and dyes in water treatment applications. Their high magnetic saturation (Ms) values, particularly in magnetite (50–60 emu/g), facilitate easy magnetic separation, which is beneficial for magnetic filtration systems. The adsorption capacity of ferrites is quantified in mg of pollutant per gram of ferrite, with magnetite nanoparticles exhibiting significant adsorption capabilities for heavy metals like Pb^{2+}, Cr^{6+}, and As^{3+}. Ferrites also show remarkable removal efficiencies, achieving 90%–95% removal rates for pollutants such as Pb^{2+}, As^{3+}, and Cr^{6+}. Additionally, ferrites like Fe_3O_4 maintain good stability across a wide pH range (4–9), enhancing their versatility for various wastewater treatment scenarios. Some ferrites, such as $NiFe_2O_4$, possess antimicrobial properties, allowing them to function as disinfectants in water treatment systems. [36,66,87–90]

Figure 9. Advantages of nano ferrites in using them for waste and waste water treatment as compared to conventional techniques.

4. Conclusions

In conclusion, ferrite synthesis techniques are essential for determining their magnetic, chemical, and physical characteristics; all synthesis techniques are widely and effectively synthesized and utilized. Sol-gel, co-precipitation, hydrothermal, and green synthesis methods are used to get the desired particle size, shape, and magnetic properties, depending on the application synthesis method utilized. Using the best synthesis method, prepared ferrites provide flexibility in health care, demonstrated by their biomedical applications, mainly in medication administration, magnetic hyperthermia, biosensing, and magnetic resonance imaging (MRI). $CoFe_3O_4$and $MnFe_3O_4$ are essential for MRI to get strong magnetic characteristics and biocompatibility, which helps MRI to contrast agents and cancer therapies. Various methods of synthesis of ferrites are discussed to get information related to antimicrobial properties and biological applications of ferrites, such as the biomedical field comprising cancer diagnosis, MRI, hyperthermia, drug delivery and release, antimicrobial properties, and wastewater treatment.

Compared with conventional drug use, the utilization of nano-ferrites has helped minimize the amount of drug needed and avoid side effects. In wastewater treatment, nano-ferrites are cost-effective and efficient compared to conventional methods. Also, nano-ferrites are promising candidates for antimicrobial and biomedical applications. The optimization of feature synthesis techniques is necessary to improve the biocompatibility, stability, and magnetic properties of ferrites for specific biomedical applications by considering green synthesis methods to avoid or minimize environmental impact while maintaining the exact cost-effectiveness and efficacy in applications such as wastewater treatment, drug delivery, and hyperthermia. Multifunctional ferrites are most important and have a high potential for new avenues in fields like theragnostic, fusing their medicinal and diagnostic properties and increasing their application in environmental sustainability and antimicrobial treatments.

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