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Mixed Nano Ferrites- Synthesis And Applications In Biomedical And Sensor Field

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Abstract: The synthesis and characterization of nano ferrites have emerged as critical research areas due to their vast potential in cutting-edge technologies. Their exceptional electrical and magnetic properties—strongly shaped by the synthesis technique—enable a broad spectrum of advanced applications. This review highlights and compares a variety of synthesis methods, including sol-gel, auto-combustion, self-combustion, co-precipitation, reverse micelle, micro-emulsion, glass crystallization, precursor-based, and hydrothermal techniques, each contributing uniquely to the structural and functional attributes of nano ferrites. We focus on mixed metal ferrites with the general formula MFe_2O_4 (where M = Cu, Fe, Mg, Mn, Ni, etc.), known for their superior performance over single-component systems. These nano ferrites exhibit remarkable properties such as high coercivity, magnetic anisotropy, Curie temperature, mechanical hardness, enhanced electrical resistivity and reduced eddy current losses. Our comprehensive analysis reveals that cation distribution, particle size, and morphology influence their behaviour. Mixed nano ferrites are versatile materials for various high-impact applications, including electronics, catalysis, sensors, data storage, and biomedicine. This review aims to understand better their synthesis strategies, core properties, and transformative potential in real-world applications.

Keywords: Mixed metal ferrites; Nano ferrites; Magnetic properties; Electrical properties; Synthesis methods; Sensor applications.

Highlights:

- Comprehensive review of synthesis techniques for mixed nano ferrites (MFe_2O_4).
- Comparison of sol-gel, auto-combustion, co-precipitation, and other methods.
- Emphasis on the influence of cation distribution, particle size, and morphology.
- Mixed nano ferrites show superior magnetic, electrical, and mechanical properties.
- Potential applications span electronics, catalysis, sensors, data storage, and biomedicine.

I. INTRODUCTION

Ferrites are a unique class of ceramic materials composed primarily of iron oxides chemically combined with one or more additional metal elements. These materials exhibit remarkable magnetic and electrical properties, making them highly valuable across a wide spectrum of electronic and electromagnetic applications [1]. Distinguished by their inclusion of transition metals and sometimes lanthanides, ferrites are typically hard, brittle, and polycrystalline, often appearing grey or black in color. Despite containing metal oxides, ferrites are electrically non-conductive, a property that enhances their utility in high-frequency electronic devices [1].

Structurally, ferrites are ferrimagnetic materials wherein oxygen anions and metal cations organize themselves within space lattices that assume various geometric configurations [2]. This ordered arrangement underpins their distinctive electromagnetic behavior. Due to their favorable combination of magnetic, electrical, and mechanical characteristics, ferrites have found widespread use in technologies such as high-density data storage systems, magneto-caloric refrigeration, magnetic resonance imaging (MRI), targeted drug delivery, radio frequency (RF) coils, transformer cores, and rod antennas [3].

A significant transformation in ferrite properties occurs when their particle size is reduced from the bulk scale to the nanoscale. At dimensions below the critical threshold for magnetic domain formation, ferrite particles enter a single-domain state, leading to pronounced changes in behavior. Nano ferrites in this regime can exhibit superparamagnetic properties characterized by moderate magnetic permeability, low coercivity, high saturation magnetization, and minimal energy loss across a wide frequency range. These enhancements are attributed to improved morphology, reduced particle size, magnetocrystalline anisotropy, higher electrical resistivity, and lower dielectric loss at elevated frequencies [4].

Based on structural differences, nano ferrites are classified into four major types: spinel ferrites, hexaferrites, garnets, and orthoferrites [5]. Among these, spinel ferrites stand out due to their tunable and versatile magnetic and dielectric properties, including low coercivity, high resistivity, significant Curie temperature, and desirable magnetic permeability. The spinel structure adopts a cubic crystalline form (Figure1) and follows the general formula MFe_2O_4, where M represents divalent metal cations such as Cu^{2+}, Ni^{2+}, Fe^{2+}, Mg^{2+}, or Al^{2+}. In this configuration, the divalent cations occupy one-eighth of the tetrahedral sites, while the trivalent Fe^{3+} cations are distributed over half of the octahedral lattice positions [1,2]. This cation distribution plays a crucial role in defining the functional properties of the spinel ferrite materials.

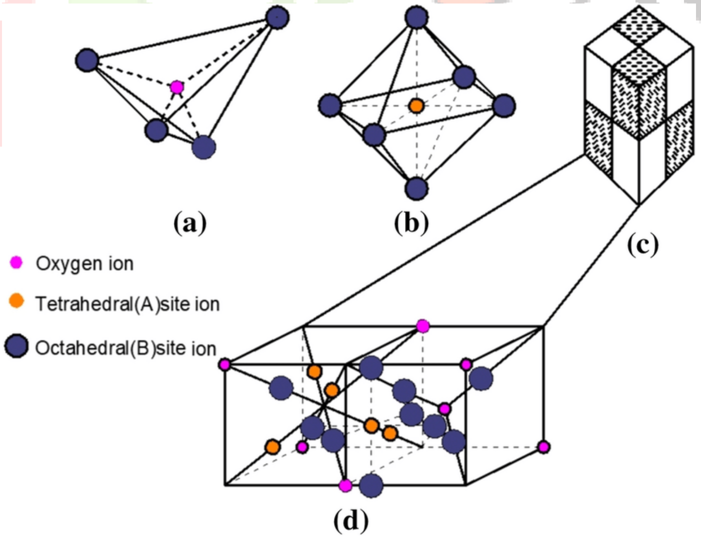

Fig.1: the crystal structure of spinel ferrite. a) tetrahedral A site; b) octahedral B site; c, d) The distribution of metal cations and oxygen ions

II. MIXED NANO FERRITES

To improve the structure, magnetic and electromagnetic properties of the ferrites, doping of dopants to nano ferrite particles play a major role to meet technological requirements. Mixed ferrites can be prepared which contain two different kinds of divalent ions like MnZnFe2O4, NiZnFe2O4 or MnZn, NiZn ferrites in these ferrites Mn, Zn and Ni, Zn are the divalent cations [6]. Mixed Nano ferrite materials have several advantages over normal ferrite particles such as improved magnetic properties like higher magnetization and coercivity due to the combination of different metal ions. Tuneable properties by varying the composition of mixed ferrites, their properties can be tailored for specific applications. Reduced toxicity-some mixed Nano ferrites have shown reduced toxicity compared to individual metal oxides, making them more suitable for biomedical applications [7].

III. **Synthesis Methods for Mixed Nano-Ferrites**

There are two ways to prepare Nano ferrite particles

i) Bottom-up synthesis

ii) Top-down synthesis

3.**1 Bottom-Up Approach**

The bottom-up approach to preparing nanostructures involves assembling materials from individual atoms or molecules into larger structures through controlled processes. This approach enables the creation of nanostructures with specific properties and functions that are often difficult to achieve by other methods. It is extensively used in nanotechnology and materials science because it allows precise control at the atomic or molecular level.

Key bottom-up methods include chemical synthesis and self-assembly. Chemical synthesis involves using chemical reactions to combine atoms and molecules into nanostructures, allowing for the design of various shapes, sizes, and compositions. Self-assembly leverages the natural tendency of atoms and molecules to spontaneously organize into structured forms due to chemical or physical forces, mimicking biological systems that naturally create intricate nanostructures. These processes can be conducted in various phases, such as gas-phase or liquid-phase synthesis, utilizing methods including sol-gel, chemical vapor deposition, wet synthesis, and biomineralization [8].

The bottom-up approach enables the production of nanostructures, such as nanoparticles, nanotubes, nanocrystals, quantum dots, and carbon nanotubes, which possess unique optical, electrical, magnetic, and catalytic properties. For instance, quantum dots can be formed by self-assembly under strain conditions to achieve uniform size and spacing, while carbon nanotubes form via self-assembly under specific chemical and temperature conditions. These nanostructures find applications across diverse fields, including medicine (biosensors, bioimaging, drug delivery), energy (catalysis, solar cells), and electronics (plasmonics, nanoelectronics) due to their finely tuned functionalities [9].

Thus the bottom-up approach has proven to be a highly effective strategy for the synthesis of nanoferrites, offering precise control over particle size, morphology, and cation distribution, all of which critically influence their structural, magnetic, and electrical properties. Techniques such as sol-gel synthesis, co-precipitation, hydrothermal methods, and combustion routes exploit atomic- and molecular-level interactions to produce uniformly distributed nanoferrites with tunable characteristics. Compared to conventional bulk synthesis, these bottom-up methodologies enable the fabrication of nanoferrites with enhanced surface-to-volume ratios, superparamagnetic behavior, and improved catalytic, dielectric, and magnetoresistive properties. Such finely tailored features broaden the application potential of nanoferrites in diverse technological fields, including high-frequency devices, magnetic storage systems, catalysis, ferrofluids, microwave absorption, and biomedical applications such as targeted drug delivery and magnetic hyperthermia. Therefore, the bottom-up synthesis of nanoferrites not only represents a crucial route for achieving advanced functional materials but also underscores their significance in developing next-generation technologies across electronics, energy, and medicine.

3.2 Sol-gel method

The sol-gel (SG) synthesis method is indeed a bottom-up approach widely recognized for preparing homogeneous nano ferrites with high purity. The process encompasses a series of chemically irreversible reactions, primarily polymerization or hydrolysis, which generate the initial sol phase. This sol subsequently undergoes condensation reactions to form a gel network, promoting growth and aggregation of the mixture. The solvent is then removed by evaporation, drying, or extraction, yielding a solid gel. Finally, calcination is applied to remove organic residues and crystallize the nanoparticles.

This SG method is advantageous for several reasons:

Low Agglomeration: Compared to other synthesis routes, the SG process tends to produce ferrites with reduced particle agglomeration. This is attributed to the controlled growth environment within the gel matrix, which restricts uncontrolled particle coalescence during synthesis and calcination steps [10], [11].

Uniform Particle Size: The gel network restricts nucleation and growth, allowing for the preparation of nanoparticles with narrow size distributions. This uniformity is crucial in tailoring magnetic and structural properties of nano ferrites, as observed in studies showing particle sizes around 20–45 nm with good size control through synthesis parameters [10], [12].

Cost-Effectiveness: The SG process operates typically at relatively low temperatures before calcination, and uses readily available precursors, making it an economical technique. The usage of waste materials as precursors (e.g., eggshells for CaO) also enhances cost-effectiveness and sustainability [13], [14].

Controlled Morphology: Parameters such as pH, precursor concentration, chelating agents, and calcination temperature allow effective tuning of particle morphology and surface characteristics. This control is reflected in various studies demonstrating tailored morphologies and magnetic properties by adjusting SG synthesis conditions and post-synthesis treatments [15], [16].

Further, SG-synthesized nano ferrites show high compositional homogeneity due to molecular-level mixing of precursors, which results in pure phase spinel structures as confirmed by XRD analyses. The calcination step ensures removal of organic residues and crystallization, which contributes to enhanced structural and magnetic properties [12], [16].

3.3 Citrate-Gel Auto-Combustion Method for Metal Ferrites

The citrate-gel auto-combustion method for synthesizing metal ferrites typically involves the following steps: First, metal nitrates (e.g., Co, Fe, Er) are dissolved in distilled water to form a clear solution, which is stirred—commonly around 300 rpm—for about 1 hour to ensure homogeneity. Then, citric acid is added as a fuel in a metal nitrate to citric acid molar ratio often around 1:3. Ammonia solution is introduced drop-wise to adjust the pH to approximately 7, promoting effective chelation and gelation. The resulting solution is heated, generally near 100 °C, to facilitate slow evaporation and gel formation over several hours (10–12 h), during which auto-combustion occurs spontaneously, producing a voluminous, black-colored powder. This as-burnt powder is further ground manually and subsequently calcined at temperatures commonly between 500 °C and 700 °C for a few hours (e.g., 4 h) in air to remove residual organic compounds and crystallize the metal ferrite phase.

This procedure yields nano-crystalline metal ferrites with a single-phase cubic spinel structure, confirmed through X-ray diffraction studies, and typically particle sizes in the nanometer range (6–45 nm, depending on conditions) with controlled morphology and magnetic properties [17], [18], [19], [20], [21], [22].

The use of stoichiometric ratios of metal nitrates to citric acid and careful pH adjustment is crucial for uniform chelation and homogeneous gel formation, which in turn influences the particle size distribution and phase purity of the final product. Auto-combustion is exothermic and self-sustaining once initiated during heating, allowing rapid synthesis of metal ferrite powders with low agglomeration and good crystallinity. Calcination temperature and duration are optimized to balance removal of organic residues with prevention of excessive grain growth [23], [24].

3.4 Top-down approach

The top-down approach to fabricating nanostructures involves starting with larger materials or patterns and systematically reducing their size to achieve nanoscale dimensions. This reduction is typically realized through various lithographic, etching, and mechanical fabrication techniques. This approach is especially prevalent in microelectronics, where macro-sized patterns are scaled down to form intricate and tiny electronic circuits.

Common top-down methods include:

Photolithography: This technique uses light to transfer geometric patterns onto a substrate, followed by chemical etching to remove the unprotected area. It remains a foundational technology in semiconductor device manufacturing, although it faces intrinsic limitations due to the diffraction limit of light, typically restricting attainable feature sizes. Recent advances explore extreme ultraviolet lithography and parallel laser micro/nanoprocessing to push beyond these constraints [25].

Electron beam lithography (EBL): EBL utilizes a highly focused beam of electrons for direct-write patterning, which allows the creation of features well below 100 nm with high precision. However, its serial nature results in low throughput and high cost, making it better suited for prototyping and small-batch production rather than mass manufacturing. Innovations in controlling electron beam parameters and resist materials continue to enhance resolution and processing efficiency , [26].

Scanning Probe Microscopy (SPM) techniques: SPM-based lithography harnesses a physical probe to manipulate surfaces at atomic or molecular resolution. Techniques such as dip-pen nanolithography, anodization lithography, and nanoshaving allow localized patterning on inorganic and organic surfaces. SPM is valuable for both imaging and nanoscale modifications but typically involves slow serial processes, limiting scalability[27].

These techniques are capable of producing nanostructures with a high degree of spatial precision and control over morphology. However, challenges remain in scaling down certain materials or patterns, limiting throughput and increasing cost. For example, photolithography is constrained by optical diffraction limits, and EBL suffers from low throughput, while SPM methods have limited scalability.

In comparison, bottom-up approaches assemble nanostructures from atomic or molecular precursors, enabling the formation of unique structures with distinctive properties via self-assembly or chemical synthesis. While bottom-up methods excel at producing complex and novel nanostructures, they often lack the precise pattern control inherent in top-down approaches.

Hybrid methods combining top-down and bottom-up strategies are gaining attention to leverage the advantages of both, enabling precise patterning with the diversity of bottom-up material synthesis [28]. Additionally, recent progress in data-driven process control and machine learning promises to address throughput and quality challenges associated with top-down nanomanufacturing .

Thus, top-down fabrication techniques such as photolithography, electron beam lithography, and scanning probe microscopy remain central to nanostructure manufacturing due to their precision and control, although each faces unique limitations in scalability and material compatibility. Both top-down and bottom-up approaches are complementary and often integrated to meet diverse nanoscale fabrication demands across scientific and technological fields [30], [31].

3.5 Ball Milling Process

The ball milling method is a widely used mechanical technique for synthesizing nanoparticles by grinding and blending materials. This process involves placing a bulk material, along with milling balls, into a rotating cylindrical container, commonly referred to as a ball mill. As the container rotates, the balls are lifted and then dropped onto the material, causing repeated impact and shear forces that fracture the particles, reducing their size to the nanoscale. Key parameters such as the size, material, and number of milling balls, the rotation speed of the mill, and the duration of milling are crucial in determining the final particle size, morphology, and phase of the nanoparticles. The impact energy from the collisions between the milling balls and the material leads to a reduction in particle size and can also induce phase transformations, enhancing material properties. Ball milling offers several advantages, including simplicity, cost-effectiveness, scalability, and environmental friendliness. It does not require hazardous chemicals or solvents, making it a greener alternative to chemical synthesis methods. The technique is versatile and can be applied to a wide range of materials, including metals, alloys, ceramics, and polymers, enabling the production of both single-component and composite nanoparticles. Nanoparticles synthesized via ball milling are utilized in various applications such as catalysis, drug delivery, electronics, and energy storage due to their unique properties. This method provides a straightforward approach to creating advanced materials with specific functionalities, making it a valuable tool in nanotechnology research and development [32], [33]

3.6 Laser ablation

The synthesis of nanoparticles using laser ablation is a physical method that involves irradiating a solid target material with a high-energy laser beam in a liquid medium or vacuum. This process leads to the formation of nanoparticles directly from the bulk material without the need for chemical reagents. The method is particularly favored for its simplicity, cleanliness, and ability to produce pure nanoparticles with minimal contamination. During laser ablation, a pulsed laser is focused on the surface of a solid target material submerged in a liquid, such as water, ethanol, or other solvents. The intense laser pulses generate a rapid, localized rise in temperature, causing the material at the surface to vaporize or melt. As this vaporized material cools and condenses in the surrounding liquid, nanoparticles form. The characteristics of the produced nanoparticles, such as size, shape, and composition, can be controlled by adjusting laser parameters like wavelength, pulse duration, energy, and repetition rate, as well as the properties of the liquid medium.

One of the key advantages of laser ablation in liquids (LAL) is the ability to produce highly pure nanoparticles, free from chemical by-products that often accompany chemical synthesis methods. This purity is crucial for applications in fields such as biomedicine, where nanoparticles are used for drug delivery, imaging, and as therapeutic agents. Additionally, LAL allows for the synthesis of a wide range of nanoparticle materials, including metals, semiconductors, and oxides, making it a versatile technique. Laser ablation also enables the production of nanoparticles with unique properties due to the rapid quenching rates, which can lead to amorphous or metastable phases not easily achievable by other methods. Moreover, the size distribution of the nanoparticles can be tuned by varying the laser parameters or by post-synthesis treatments, such as centrifugation or filtration. Overall, the synthesis of nanoparticles using laser ablation is a powerful technique that provides precise control over nanoparticle production, offers high purity, and is versatile across different materials and applications. It is widely used in research and industry for developing advanced materials with tailored properties for specific applications [34].

3.7 Green synthesis of Nano ferrites

The green synthesis method is a sustainable and eco-friendly approach to synthesizing nanoparticles, using natural materials and environmentally friendly processes. This method involves selecting natural materials, such as plant extracts, microorganisms, or biomolecules, as reducing agents and stabilizers. The natural material is then mixed with a metal salt solution under suitable conditions, such as temperature, pH, and concentration, to form a reaction mixture. The natural material reduces the metal ions, forming nanoparticles, which then grow and are stabilized by the natural material. Finally, the synthesized nanoparticles are purified and characterized using various techniques.

Green synthesis offers several advantages over physical and chemical methods, including non-toxicity, pollution-free, environmental friendliness, economical, and sustainability. However, challenges and limitations of this method include the availability of raw materials, reaction time, and quality of final products, such as particle size and homogeneity.

Overall, green synthesis is a promising approach for sustainable nanoparticle production, with potential for advancement in various fields. This method provides a viable alternative to traditional methods, reducing the environmental impact and improving the sustainability of nanoparticle synthesis[35].

IV. Applications :

4.1 Bio-Medical Applications:

Magnetic nanoparticles (NPs) have unique properties making them suitable for nanomedicine applications such as drug delivery, imaging, and hyperthermia. Iron oxide and cobalt-ferrite (Co-Fe) NPs are commonly used, with Co-Fe NPs showing larger magnetic anisotropy. However, their toxicity needs to be understood for successful application. Studies have shown that surface coating can reduce toxicity, and predictive toxicology approaches can help forecast toxic effects. This study explores the toxicological effects of Co-Fe NPs on cell viability and oxidative stress, using data mining and knowledge discovery to develop a predictive model of NP toxicity. The model predicts the relative hierarchy of variables such as concentration, cell type, and exposure duration, providing a multi-dimensional perspective on NP toxicity[36].

4.2 Magnetic thermotherapy:

Magnetic hyperthermia, a cutting-edge cancer treatment, leverages magnetic nanoparticles (MFNPs) to generate heat and selectively target tumor cells when exposed to an alternating magnetic field (AMF). Despite its clinical approval and registration, the technique faces limitations, including inefficient heat transfer.

Recent breakthroughs have focused on optimizing MFNP properties to enhance heating efficiency. Researchers have explored various strategies, such as tailoring size, morphology, composition, and surface modification, as well as exchange-coupled and assembled MFNPs. Notably, innovative designs like vortex-domain nanorings (FVIOs) and exchange-coupled core-shell MFNPs have demonstrated significantly improved heating performance.

While these advancements hold promise, further research is crucial to overcome existing challenges and unlock the full potential of magnetic hyperthermia. Continued innovation in MFNP design and optimization is essential to enhance treatment efficacy and pave the way for future applications[37].

4.3 Magnetic resonance imaging (MRI)

Magnetic Resonance Imaging is a crucial diagnostic tool in hospitals, relying on contrast agents to enhance image quality. Superparamagnetic iron oxide nanoparticles (SPIONs) are commonly used as MRI contrast agents, but their tendency to aggregate in water or tissue fluid limits their application. To overcome this, coating SPIONs with polymers like polyethylenimine (PEI) or poly(ethylene glycol) (PEG) improves their stability, biocompatibility, and circulation time.PEI-coated SPIONs have shown promise as MRI contrast agents, but PEI's toxicity limits its use. PEG, on the other hand, is a biocompatible and non-toxic polymer widely used in pharmaceuticals. Recent studies have combined PEG with PEI for gene delivery, but PEG-modified PEI-coated SPIONs have not been explored for MRI contrast agents.This highlights the potential for developing PEG-modified PEI-coated SPIONs as safe and effective MRI contrast agents, combining the benefits of both polymers [38].

4.4 Drug delivery

The application of magnetic nanoparticles (MNPs) in targeted drug delivery has revolutionized the field of medicine. MNPs have shown great promise in delivering drugs to specific sites in the body, reducing side effects and improving therapeutic outcomes. Magnetic nano ferrite particles can be used as a delivery vehicle for drugs, entrapping them in their matrix and releasing them at the target site.

4.5 Advantages of magnetic nano ferrites

Targeted drug delivery: Magnetic nanoferrite particles can be guided to specific sites in the body using external magnetic fields, ensuring that the drug is delivered directly to the affected area.

Controlled release: Magnetic nano ferrite particles can be designed to release drugs in response to specific stimuli, such as changes in pH or temperature.

Biocompatibility: Magnetic nanoferrite particles are generally non-toxic and biocompatible, making them suitable for use in the body [39], [40], [41].

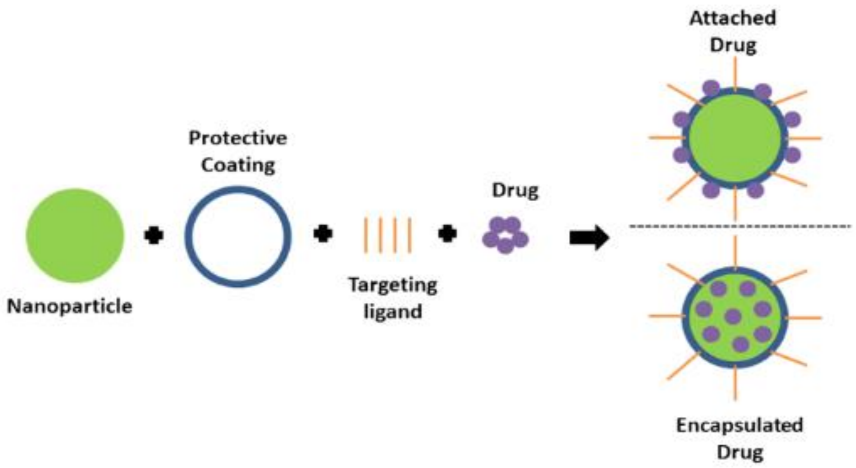

Fig 3: Nanoparticles in biomedical applications [Image is adopted from Karrina McNamara and Syed A. M. Tofaildepartment of Physics, Bernal institute, University of Limerick, Limerick, Ireland].

Table I: Survey on synthesis methods and surface functionalisation of ferrite NPs in biomedical applications.

Ferrite	**Synthesis method**	**Functionalization**	**Application**	**Ref no.**
Manganese – Magnesium	SG	Scandium	Magnetic resonance imaging & Biosensor	[42]
Cobalt	SG	Transition metals	Drug delivery	[43]
Zinc	CCP	Chitosan and PEG	Magnetic resonance imaging	[44]
Nickel	GS	Glycine	Leishmaniasis treatment	[45]
Cobalt	HT	Copper	Antibiotic medicines	[46]
Manganese Zinc	CCP	Chitosan	Hyperthermia	[47]
Cobalt	GS	Zinc	Removal of Pb2+ from water and magnetic hyperthermal therapy	[48]
Silver	CS	--	Antimicrobial activity	[49]
Zinc	ST	PEG	Drug delivery technique for improved cancer treatment	[50]
Manganese –Magnesium-	CS	---	Magnetic hyperthermia	[51]

Cobalt				

SG: Sol-gel, CCP: chemical co-precipitation method, BS: green synthesis, HT: hydrothermal, CS: combustion synthesis, ST: solvothermal.

4.6 Sensor applications

Recent advances have established ferrite nanoparticles as robust materials for gas and humidity sensors across various industries. Spinel ferrites, due to their unique crystal structure and high surface area, offer enhanced sensitivity and selectivity. Zinc, cobalt, nickel, and manganese-doped ferrites are at the forefront, benefiting from controlled synthesis methods such as hydrothermal, co-precipitation, and sol–gel techniques, which enable the precise tuning of particle size and surface properties for improved sensor performance [52].

Fabrication of cobalt ferrite nanoparticles and their calcination at optimal temperatures has yielded sensors with strong sensitivity to ethanol and LPG gases; for example, smaller $CoFe_2O_4$ particles demonstrate rapid response and high sensitivity to low concentrations of LPG, with response times measured in mere seconds. Porous structures further enable operation at room temperature, broadening practical utility. In related research, manganese oxide-doped ferrite nanoparticles have been utilized in inkjet-printed sensors, offering low detection limits and reliable operation for pharmaceuticals and biological analytes .

The selectivity of ferrite nanoparticles has also made them suitable for agricultural and environmental monitoring. Investigations show that cobalt-doped zinc ferrite can effectively sense hazardous herbicides like metribuzin, using electrochemical methods such as impedance spectroscopy. Ferrite-based sensors display remarkable stability, rapid response, and low cost, contributing to their deployment in pollution monitoring and toxic gas detection [53] [54].

Overall, integrating nanostructured ferrites with modern synthesis and detection technologies delivers sensors that are compact, energy-efficient, and capable of precise measurement even at low operating temperatures. This positions ferrite nanomaterials as leading candidates for next-generation sensor development, with ongoing research focusing on further performance optimisation through elemental doping and hybrid material engineering [55].

V. Conclusion

In conclusion, this review underscores the remarkable potential of mixed nano ferrites across diverse application domains, particularly in biomedicine and sensor technology. The synthesis and processing techniques play a pivotal role in determining the structural, electrical, magnetic, and mechanical properties of these materials. As the particle size transitions from bulk to the nanoscale, properties such as surface-to-volume ratio, porosity, and overall reactivity are dramatically altered—directly influencing their functional performance. Emerging research consistently shows that mixed nano ferrites outperform their single-metal counterparts, offering enhanced functionality through compositional tuning. Strategic doping with transition or rare earth metals significantly boosts key attributes like saturation magnetisation, coercivity, and electrical resistivity. These optimised characteristics make them ideal candidates for high-performance applications in both medical diagnostics and electronic systems. Crucially, the ability to precisely tailor the composition, size, and structure of mixed nano ferrites provides a powerful toolkit for engineering materials with application-specific performance profiles. Their unique crystal architectures and tunable properties—especially when enhanced through doping—position them as a highly versatile platform for next-generation technologies requiring smart, efficient, and multifunctional materials.

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