

REVIEW PAPER

Recent advancements in the synthesis and applications of doped-undoped metal ferrites nanoparticles: A review

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Received: 18 December 2024; Accepted for publication: 29 August 2025

Abstract. Over the past decade, there has been a significant surge in research on the generation of metal ferrites and transition metal doped ferrites the numerous novels use for these materials have been discovered. Ferrites are widely used because they can easily form to have convinced chemical, optical, magnetic, electrical, and structural properties by employing suitable synthesis methods. This work reviews sol-gel, hydrothermal, co-precipitation, and micro-emulsion technologies. Due to these characteristics, it is useful for possible applications in biomedicine, sensors, pigments, photoluminescence, photocatalysis, water purification, and antibacterial agents. Here most relevant applications such as sensors, biomedical applications, photocatalysis, photoluminescence, magnetic applications, coloring, and supercapacitor are reported in this study.

Keywords: metal ferrites, sol-gel, hydrothermal, supercapacitor, sensors.

Classification numbers: 2.4.2, 2.4.1.

1. INTRODUCTION

One kind of ceramic substance that has special magnetic properties is ferrites. In essence, they are made up of ferric oxide mixed with the oxides of different metals like zinc, manganese, or nickel [1]. These are ferromagnetic ceramic compound materials that are electrically non-conductive. They are made up of different combinations of iron oxides, such as magnetite (Fe_3O_4) and hematite (Fe_2O_3), and the oxides of other metals. Because ferrites are ferromagnetic, they can be magnetized to form permanent magnets and are drawn to magnetic fields [2]. With the general chemical formula MFe_2O_4 , where M specifies a divalent metal ion typically, transition metal ions like Mn, Fe, Mg, Co, Cu, Ni, and Zn spines have a distinctive metal oxide structure [3].

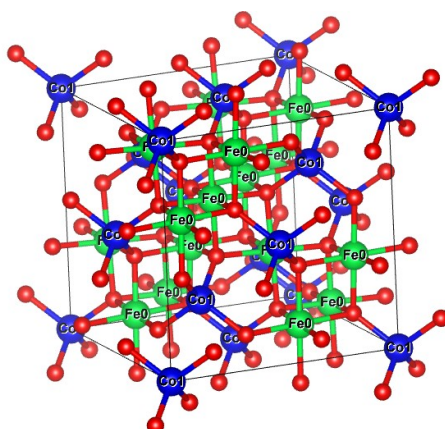


Figure 1. Crystal structure of CoFe_2O_4 .

Ferrites are classified into four main types based on their crystal structures:

- Spinel (cubic crystal structure),
- Garnet (cubic crystal structure),
- Hexaferrites (hexagonal crystal structure),
- Orthoferrites (orthorhombic crystal structure).

Ferrites are classified into soft and hard types based on resistance to demagnetization; soft ferrites are easily magnetized/demagnetized, while hard ferrites resist both and are used in permanent magnets [4, 5]. Their physicochemical properties are strongly influenced by the arrangement and distribution of metal cations in the crystal structure. Nanocrystalline ferrites attract wide interest across multiple fields due to their enhanced reactivity and improved thermal, mechanical, optical, electrical, and magnetic properties compared to bulk materials [6, 7]. These properties arise from high surface-to-volume ratio and dependence on both composition and particle size/morphology, which can be precisely tuned [8, 9]. Table 1 summarizes the advantages of ferrites [4, 6–10].

Table 1. Property and advantages of ferrites.

Property	Advantages	Refs.
High resistance to high current	Suitable for high-power applications	[11]
Low eddy current losses over many frequencies	Efficient at various frequencies	[12]
High permeability	Ideal for high frequency transformers and adjustable inductors	[13]
Low electrical conductivity	Prevention of eddy currents	[14]
High magnetic permeability	Allow storage of large energy in a small space	[15]
Low power loss at high frequencies	Excellent for power electronics to telecommunication devices	[16]
Ability to withstand high frequencies and have a long lifespan	Durable and long lasting	[17]
Ability to excite or filter high frequencies without demodulating the signal	Useful for signal processing applications	[18]

Ability to increase the switching frequencies of ferrite taps or speakers	Enables versatile applications in electronics	[19]
Power efficiency	Suitable for production of medical equipment and telecommunications equipment	[20]

Overall, ferrites have unique properties that make them suitable for various applications, ranging from transformers and inductors to wireless charging systems and medical equipment. Ferrites hold significance from both practical and theoretical perspectives, offering a fascinating array of properties. The magnetic nanoparticles (MNPs) with the thermal and chemical stability of CoFe_2O_4 , MnFe_2O_4 , CuFe_2O_4 , ZnFe_2O_4 , and NiFe_2O_4 have prompted an abundance of research [20-22]. These nanoparticles (NPs) have unique optical, electrical, dielectric, magnetic, and structural characteristics that make them useful in a variety of technological applications [20, 22, 23].

2. SYNTHESIS OF METAL FERRITES

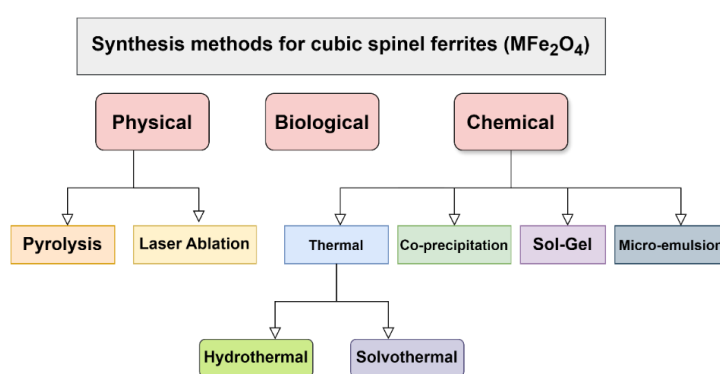


Figure 2. Different synthesis methods of metal ferrites.

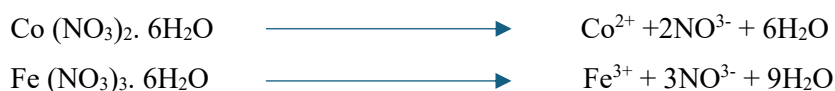
Various methods are now employed to generate nanoparticles, such as the Sol-Gel method, Hydrothermal, Co-Precipitation method, Micro emulsion, solvothermal, and solid-state methods. The synthesis of ferrite nanoparticles has not yet been achieved through a universal method, and each approach has pros and cons of its own [24]. As these magnetic ferrites are used as catalysts, their shape, structure, and other properties are greatly influenced by the preparation method used to produce them, which may influence the materials' catalytic activity [25]. So, the impact of the preparation method on NPs is among the most intriguing subjects to research. The sol-gel, auto-combustion method, hydrothermal method, co-precipitation method, and micro-emulsion method are the most popular methods for synthesis of spinel ferrite materials.

2.1. Sol-gel and auto-combustion method

The ability to regulate size and shape makes MFe_2O_4 MNPs with nanostructures useful for engineering applications. Although the sol-gel process is easy to use and inexpensive, its primary drawback is the low purity of the final product. To produce high purity and crystalline nanostructures, thermal treatment is required. The kind of precursors that were present in the original colloidal solution had a major impact on the shape and crystallinity of the nanoparticles made using this technique [26]. In this process, sol is produced by adding the precursor solution to processes that take place during polymerization or hydrolysis. Simple solvent evaporation is utilized to prepare MFe_2O_4 NPs after the gelation process, which uses polymer addition or sol

condensation to gel. This method's primary advantages over other approaches are its low temperature, highly regulated synthesis, and easy experiment setup

The formation of nanomaterial is based on transition of colloidal solution called as sol getting network like gel. The mechanism with synthesis of CoFe_2O_4 : first metal precursor dissolves in water or ethylene glycol like solvent and release ions



The chelating agent citric acid used to chelate the reaction and helps to form coordination complexes helps to form stable metal organic solution.



For the polymerization called as simply gel formation, the metal precursor solution gel gets heated around $100\text{ }^\circ\text{C}$ to $120\text{ }^\circ\text{C}$.



The uniform distribution of metal ions throughout the gel is controlled during this process. On heating around $400\text{ }^\circ\text{C}$ to $800\text{ }^\circ\text{C}$ organic contents get burn off.



The temperature of the flame may vary from 600 to $1350\text{ }^\circ\text{C}$ during combustion [27, 28]. The fundamental advantages of using sol-gel combustion include small particle size, excellent chemical homogeneity, a very pure and crystalline product, and easy control over the final spinel's stoichiometry. By altering the reactant ratio, pH, reaction conditions, and heat source, ferrites can take on various morphologies, including nanospheres, hollow nanocages, and nanorods [29]. According to C. Joseph Prabagar *et al.* [30], auto combustion synthesis creates ceramic particles in a non-uniform way due to its extraordinarily high temperature and reaction rate. According to high resolution electron microscopy (HRTEM) images of $\text{Co}_{1-x}\text{Mn}_x\text{Fe}_2\text{O}_4$ nanoparticles (where $x = 0.0, 0.2, 0.4, \text{ and } 0.6$) size range of ferrite grains was observed to be 15.6 to 20 nm [30]. Crystallites are spherical in form and less aggregated.

2.2. Hydrothermal method

The hydrothermal method uses high-pressure reactors or autoclaves to achieve high pressures at high temperatures, controlling size and shape and eliminates the need for post-annealing treatment [31]. The flame's temperature during combustion can range from 600 to $1350\text{ }^\circ\text{C}$. A extremely pure and crystalline result, small particle size, outstanding chemical homogeneity, and simple control over the final spinel's stoichiometry are the main benefits of employing sol-gel combustion. Nanospheres, hollow nanocages, and nanorods are among the different shapes that ferrites can adopt by varying the reactant ratio, pH, reaction conditions, and heat source [32].

This method works especially well for producing hollow, precisely shaped spinel ferrite particles, like cubic and nanoflowers [33]. It is crucial to highlight that this approach's nucleation rate and reaction kinetics are strongly influenced by the synthesis temperature. It is well-known that reagents can change at high temperatures in terms of solubility and reactivity [34]. As a result,

these changes offer more ways to produce a variety of morphologies and phases, including metastable ones, which are impossible to achieve at low temperatures. Consequently, this technique has been widely used to produce a variety of highly crystalline and pure target ferrites. According to this viewpoint, the advantage of this approach is that it enables the adjustment of reaction temperature, duration, dopants, and other factors to influence particle size, shape, and other physical characteristics [35, 36]. According to Sami Ullah Rather *et al.* [37], the Scanning Electron Microscope (SEM) profile seen in Figure 3 (a-d) depicts zinc ferrite ($\text{ZnFe}_{2-x}\text{Al}_x\text{O}_4$) nanoparticles doped with aluminum. The profiles (a-d) in this case correspond to ferrite samples with $x = 0.0, 0.3, 0.6,$ and 0.9 . Every ferrite image has a scale bar of 100 nm. This literature claims that the addition of ions alters the ferrite sample's particle size. Sample grain size reduces with increasing Al inclusion.

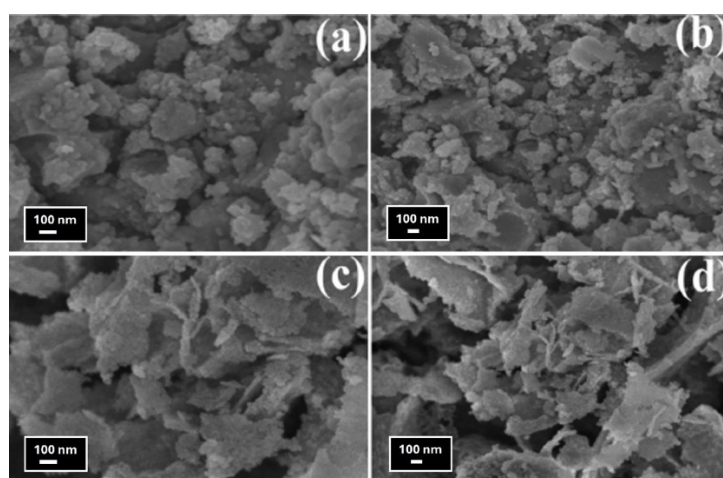


Figure 3. SEM images with a scale bar of 100 nm of the $\text{ZnFe}_{2-x}\text{Al}_x\text{O}_4$ ($x = 0.0, 0.3, 0.6,$ and 0.9) [37].

2.3. Co-precipitation method

Co-precipitation is a cost-effective and widely used method for synthesizing MFe_2O_4 nanoparticles with high purity, homogeneity, and controllable size by reacting metal salts with a base under controlled conditions (pH, temperature, time, and precursor ratio) [38]. It enables large-scale production and easy dispersion in aqueous media, making it industrially significant [39, 40]. However, challenges include limited control over morphology, particle size distribution, and low crystallinity, which often requires post-heat treatment [41, 42]. Typically, metal salts (nitrates/chlorides) are dissolved, precipitated, washed, and calcined to obtain crystalline oxides, with synthesis conditions strongly influencing particle growth and aggregation [43, 44]. FE-SEM studies reveal aggregated grains with distinct crystallinity, where uneven particle formation is attributed to interparticle interactions and reduced band gap energy [45].

2.4. Micro emulsion method

Microemulsions are isotropic, stable mixtures of surfactant, oil, and water that enable immiscible liquids to coexist, commonly used for synthesizing magnetic nanoparticles via direct (o/w) and reverse (w/o) methods [46, 47]. This technique allows precise control over particle size, morphology, and surface properties by adjusting synthesis parameters, with surfactant

concentrations above the critical micelle concentration (CMC) [48]. It is environmentally friendly, low-temperature, and allows surfactant recycling, but drawbacks include poor crystallinity, high solvent use, and polydispersity due to slow nucleation [49, 50]. Spinel ferrites such as MFe_2O_4 ($M = Co, Ni, Zn$) and Mn–Zn ferrites have been synthesized using this method. Studies report spherical and elongated nanoparticles with agglomeration, where size trends from XRD and SEM correlate, and increased dopant levels (e.g., Cd, Er) enhance aggregation and surface area, improving photocatalytic potential [51].

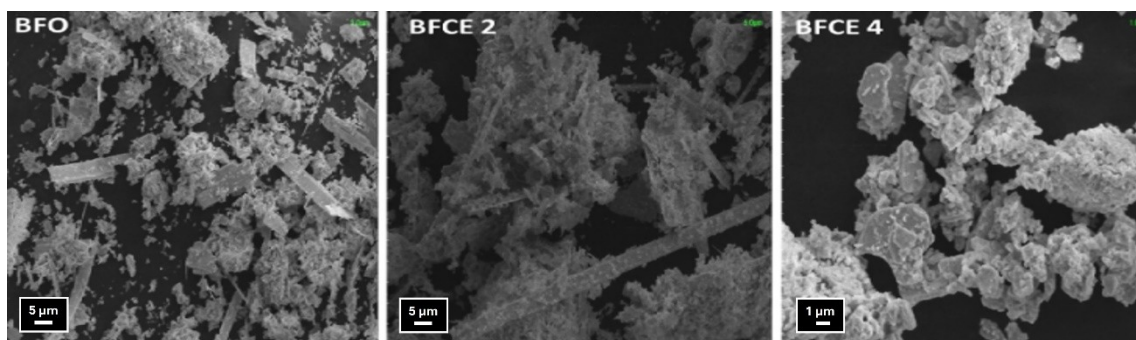


Figure 4. SEM micrographs of pristine and $Bi_{1-x}Cd_xFe_{1-y}EryO_3$ nanoparticles [51].

Table 2. Comparative analysis of synthesis methods for metal-doped ferrite nanoparticles.

Synthesis Method	Advantages	Drawbacks	Particle Size Range	Crystallinity	Common Applications	Refs.
Sol-gel	Low temp, size control, compositional purity	Requires calcination, long process	41-63 nm	Medium-High	Photocatalysis, sensors	[52]
Hydrothermal	High purity, shape control	Needs high pressure & temperature	20 nm	High	Drug delivery, supercapacitors	[53]
Co-precipitation	Simple, scalable, low-cost	Poor crystallinity, post-treatment needed	19-80 nm	Low-Medium	Magnetic materials, catalysis	[54]
Micro-emulsion	Narrow size distribution, tuneable shape	Expensive surfactants, limited scalability	2–15 nm	Low	Drug delivery, photocatalysis	[55]

3. SUMMARY OF SYNTHESIS METHODS OF METAL DOPED FERRITES

The synthesis of metal-doped ferrites has been extensively explored using various methods to tailor their structural, magnetic, and electrochemical properties as described in Table 2. Each synthesis route significantly influences the particle size, crystallinity, morphology, and dopant distribution within the ferrite matrix. Among the widely used techniques, the sol-gel and auto-combustion methods offer excellent chemical homogeneity and fine particle control. The hydrothermal method enables the growth of highly crystalline nanoparticles at relatively low

temperatures. Co-precipitation is preferred for its simplicity, scalability, and cost-effectiveness, while the micro-emulsion method provides uniform and ultra-fine particles due to its nanoreactor-like environment. A comparative summary of these methods, materials, dopants, and related references is provided in the following Table 3.

Table 3. Overview of synthesis methods for metal-doped ferrites.

Synthesis Method	Material	Dopant	Refs.
Sol-gel and auto-combustion method	CoFe ₂ O ₄	Ag	[56]
	CoFe ₂ O ₄	Zn, Cu, Mn	[57]
	CoFe ₂ O ₄	Mg, Mn	[58]
	Mg _x Co _{1-x} Fe ₂ O ₄	Mg	[59]
	CoFe ₂ O ₄	Ni	[60]
	Ni _{0.2} Cu _x Zn _{0.8-x} Fe ₂ O ₄	Cu ²⁺	[61]
	M _{0.25} Ni _{0.15} Cu _{0.25} Co _{0.35} Fe ₂ O ₄	Mg ²⁺ , Mn ²⁺	[62]
	Ni _{0.5} Co _{0.5-x} Zn _x Fe ₂ O ₄	Zn	[63]
	MgFe ₂ O ₄	Zn	[64]
Hydrothermal	Ni _x Zn _{1-x} Fe ₂ O ₄	Ni	[65]
	Mg _{1-x} Ni _x Fe _{2-x} Cr _x O ₄	Ni, Cr	[66]
	Ni _x Mg _{1-x} Fe ₂ O ₄	Ni	[67]
	Cd _x Zn _{1-x} Mg _{0.25} Fe _{1.75} O ₄	Cd-Zn	[68]
	NiAl _y Fe _{2-y} O ₄	Al	[69]
	Co _{1-x} Ni _x Fe ₂ O ₄	Ni	[70]
	Co _{1-x} Zn _x Fe ₂ O ₄	Co	[71]
Co-precipitation method	Mn _{0.1} Mg _{0.2} (Co,Ni,Zn) _{0.7} Fe ₂ O ₄	Co, Ni, Zn	[72]
	Al _x Zn _{1-x} Fe ₂ O ₄	Al	[73]
	Ca _{1-x} Cu _x Fe ₂ O ₄	Cu	[74]
	Co _{1-x} Zn _x Fe ₂ O ₄	Zn	[75]
	Ni _{1-x} Cu _x Fe ₂ O ₄	Cu	[76]
	Ni Fe ₂ O ₄	Mn	[77]
	Cu _{1-x} Zn _x Fe ₂ O ₄	Zn	[78]
Micro-emulsion method	CoFe ₂ O ₄	Ni	[79]
	Ni _{0.3} Zn _{0.7} Pr _x Fe _{2-x} O ₄	Pr	[46]
	Co _{0.5} Zn _{0.4} Ca _{0.1} Fe ₂ O ₄	Ca	[80]
	BiFeO ₃	Ni-Co	[81]

4. VARIOUS APPLICATIONS OF METAL FERRITES

During the last few years, rigorous research work has been dedicated on metal ferrites and its nanocomposites because it has wide applications in various disciplines like fuel cell, biosensors, photocatalysis, photoluminescence, Supercapacitors, humidity-sensors, catalysis, magnetic refrigeration, and the development of permanent magnets [23, 82-84] as depicted in the schematic diagram shown in Figure 5. Here are some specific applications of ferrites based on the provided search results:

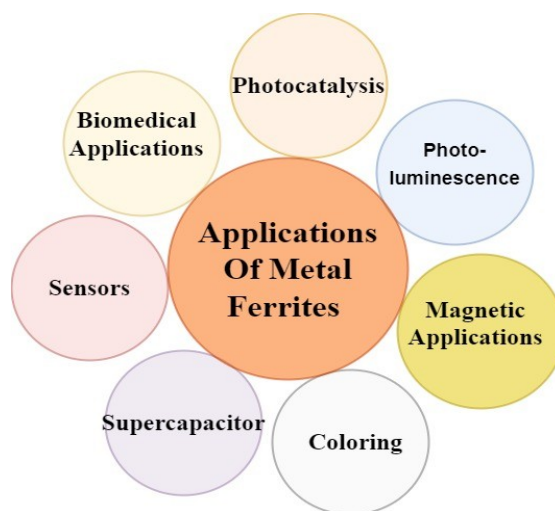


Figure 5. Different applications of metal ferrites.

4.1. Sensors

Ferrites containing Co, Zn, Mg, Mn, Ni, and Cu are widely used in sensors due to their high chemical stability, strong mechanical properties, and diverse sensing capabilities based on electrochemical, optical, piezoelectric, and magnetic principles [85, 86]. They are effective in gas sensing for hazardous detection with both qualitative and quantitative analysis, and are also explored for temperature sensing in MRI thermometry [87–90]. Spinel ferrites (MFe_2O_4) combined with conductive materials like graphene, carbon nanotubes, and carbon nitrides enhance sensitivity and repeatability, while coupling with noble metals and other compounds further improves performance [91, 92]. These materials enable low-cost, portable electrochemical sensors, especially with screen-printed electrodes, highlighting strong application potential [93]. Studies using solution combustion methods confirm structural properties, though sensing performance varies, and ongoing research focuses on improving synthesis and expanding applications [94–97].

4.2. Medical applications

Ferrites have attracted attention in the biomedical field due to their improved magnetic properties, which are beneficial for imaging, diagnosis, and treatment. They are used in a variety of medical applications, including biosensors, magnetic separation, targeted medication delivery, MRI, nanorobots, and magnetic hyperthermia [98]. Ferrites are particularly attractive for biomedical applications because they are composed of elements that are required metabolic minerals in the body, such as Fe, Mn, and Zn, which reduces the risk of toxicity [99]. To increase

biocompatibility, certain ferrites—such as those containing Ni, Co, or Zn—need to be coated because of their intrinsic toxicity. Theranostics, a developing field of study, focuses on creating multifunctional ferrites that can perform multiple functions [100]. Despite the promising results, ferrites have not yet advanced to the clinical trial stage for most applications. Ferrite nanoparticles can be used as sensitive probes for detecting various biomolecules and pathogens [101]. Ferrites can be used to kill or inhibit the growth of bacteria and other microorganisms. Zinc ferrite nanoparticles (Mn-ZnFe₂O₄ NPs) have been shown to have bactericidal potential and activity that encourages wound healing [102]. Priyambada Sahoo *et al.* [103] reported that zinc ferrite (ZnFe₂O₄) nanostructures have strong magnetic features, low toxicity, and good biocompatibility. Relative to other transition metal ferrites, their Curie temperature is lower, enabling tailoring to the therapeutic window of 43–46 °C for magnetic hyperthermia applications. Nanostructures based on zinc ferrite have been frequently used in preclinical investigations on mouse models to demonstrate how chemotherapy and magnetic hyperthermia can work together to kill cancer cells. The biocompatibility, magnetic properties, and tuneable features of ferrites have made them highly promising for usage in a range of medical applications [104]. They are being investigated for the following biomedical uses:

- Diagnosis: Ferrites are useful as contrast agents for magnetic resonance imaging (MRI), which improves the visibility of particular tissues and organs [105].
- Magnetic hyperthermia: Ferrite nanoparticles can generate heat when exposed to an alternating magnetic field, which can be used to destroy cancer cells [106].
- Drug and gene delivery: Ferrites can be functionalized to target specific cells or tissues, improving the delivery of therapeutic agents [107].
- Catalysis: Ferrites are used in catalytic applications, including gas sensing mechanisms and magnetic nanocarriers for medical application.

4.3. Photocatalysis

Ferrites are cost-effective, magnetically recoverable, chemically stable materials with narrow bandgaps, making them suitable for photocatalysis [108]. Spinel ferrites such as ZnFe₂O₄, CoFe₂O₄, NiFe₂O₄, and CuFe₂O₄ exhibit high porosity and efficient charge separation, enabling degradation of organic pollutants under visible light. Their activity can be enhanced via doping, composite formation, and morphology control [109, 112–113]. ZnFe₂O₄ is especially promising for water treatment due to its small bandgap and easy recovery [110], while Ni-doped Mg–Zn ferrites show improved tetracycline degradation via reactive species like superoxide radicals and holes [111].

4.4. Photoluminescence

Ferrites exhibit notable photoluminescence useful in sensing and imaging applications [114]. Mixed spinel nanostructures like CoFe₂O₄, NiFe₂O₄, and ZnFe₂O₄ show visible emission due to charge transfer between Fe³⁺, M²⁺ (Co, Ni, Zn), and O²⁻ ions [115–117]. Emission peaks arise from oxygen vacancies (~418 nm) and Fe³⁺ transitions (~460 nm), while doping (e.g., Cu in ZnFe₂O₄) enables tunable emission intensity [118–120].

4.5. Magnetic application

Ferrites are widely used in magnetic devices such as speakers, motors, sensors, and memory systems due to their hysteresis properties [122, 123]. Although less effective than NdFeB magnets in magnetic refrigeration, they contribute as magnetic field sources and recyclable materials, supporting eco-friendly cooling technologies [121, 125]. Applications extend to electronics, appliances, and energy systems, including motors, MRI, and wind turbines [124], highlighting their broad industrial relevance [126].

4.6. Coloring

Ferrites, derived from iron oxides with partial metal substitution during calcination, are widely used as coloring agents in pigments, coatings, plastics, and inks; for example, manganese ferrite acts as a black pigment and zinc ferrite as a yellow pigment [127]. Spinel ferrites are particularly valued as opacifiers and colorants due to their tunable optical properties, enabling versatile coloring in paints and glasses [127]. In ceramics, CoFe_2O_4 – ZnFe_2O_4 pigments enhance durability by forming cationic soaps in corrosive environments, improving binder strength [128, 129]. The color of ZnFe_2O_4 depends on annealing temperature and particle size, as higher temperatures reduce defects and improve crystal site symmetry, leading to more defined colors [130]. Tailoring cation distribution within the spinel lattice (e.g., Zn^{2+} in A sites, Fe^{3+} in B sites) further controls pigment properties [131]. Overall, ferrites show strong potential for advanced coloring applications with improved heat stability, photocatalytic activity, and use in nanostructured sensors and technologies.

4.7. Metal ferrites for supercapacitor application

The growing demand for compact, lightweight, and cost-effective electronic devices has intensified research in energy storage, highlighting ferrites as promising electrode materials for supercapacitors and next-generation devices due to their high energy and power density [132, 133]. Their advantages—high capacitance, energy storage capacity, long cycle life, and low cost—make them suitable for sustainable applications [134]. For instance, $\text{Mn}_{0.95}\text{Zn}_{0.05}\text{Fe}_2\text{O}_4$ showed a high specific capacitance of 829 F g^{-1} and energy density of 77.5 Wh kg^{-1} at 0.5 A g^{-1} , with $\sim 20\%$ capacity fading after 8000 cycles, attributed to Zn^{2+} substitution and enhanced redox activity [135]. Similarly, NiFe_2O_4 nanoparticles and ternary ferrites synthesized via solution and sol-gel methods have been explored as efficient electrodes [136], while $\text{MnFe}_2\text{O}_4/\text{MoS}_2$ nanocomposites significantly improved capacitance from 600 to 2093 F g^{-1} and demonstrated practical applicability in asymmetric supercapacitors [137]. Ferrite nanostructures exhibit fast, reversible redox reactions, making them effective for energy storage applications [138].

Beyond energy storage, spinel ferrite nanomaterials display multifunctional properties, including gas sensing, antimicrobial activity, hyperthermia, photocatalysis, tunable photoluminescence, magnetocaloric effects, and stable pigment behavior [139, 140]. Their composites, such as $\text{MnFe}_2\text{O}_4/\text{MoS}_2$ and NiFe_2O_4 , offer high capacitance and durability, supporting applications in sensors, biomedicine, environmental remediation, and energy technologies [141]. Table 4 summarizes recent developments in spinel ferrite nanomaterial applications.

Table 4. Overview of spinel ferrite nanomaterials in multifunctional applications.

Application area	Material /System	Key metrics	Performance	Refs.
Sensor	NiFe ₂ O ₄	Sensitivity: ~70.6 nA/μM/cm ² ; LOD: ~23.9 nM	Excellent aqueous nitrite sensing (electrochemical)	[142]
	Ni _x Mn _{0.25-x} Mg _{0.75} Fe ₂ O ₄ (x=0.20)	Sensitivity: ~707 % to NO ₂	Superparamagnetic, elevated temp, fast response	[143]
	ZnFe ₂ O ₄ thin film	Response: ~84 % (500 ppm ethanol), ~12 s time	Fast, repeatable ethanol detection at ~340 °C	[144]
	Co _{0.25} Ba _{0.75} Fe ₂ O ₄	Sensitivity: ~79.2 % (NO ₂) at room temperature	Ambient, selective sensing	[145]
Medical	ZnFe ₂ O ₄	SAR: 800– 4300 W/g Fe; Safe ≤250 μg/mL	Magnetic hyperthermia & antimicrobial (<i>E. coli</i> , <i>S. aureus</i>); high biocompatibility	[103]
	Mn–ZnFe ₂ O ₄	SAR: ~1200 W/g Fe	Outperforms ZnFe ₂ O ₄ in heating efficiency	[146]
	ZnFe ₂ O ₄ /ZnO	Antimicrobial: ~99–100 %	Effective vs. bacteria/fungi; good for wound healing & implants	[147]
Photocatalysis	MnFe ₂ O ₄ /MoS ₂ composite	Degradation: ~2093 F/g	Best tetracycline removal; high activity	[148]
	ZnFe ₂ O ₄ /MWCNTs	Degradation: ~98.3 % (TC, 120 min)	Excellent reusability & stability	[149]
	NiFe ₂ O ₄ /CeO ₂ /GO	Degradation: ~95 % (TC)	Strong performance under visible light	[150]
Photoluminescence	CoFe ₂ O ₄	Peaks: ~430 nm, 465.8 nm	Oxygen vacancies; tuneable by doping and annealing	[151]
	ZnFe ₂ O ₄	Peaks: 367– 376 nm, 645– 850 nm	Defect-induced dual PL emission	[152]
	NiFe ₂ O ₄	Peaks: ~350, 680– 820 nm	Emission intensity increases with synthesis temp	[119]
Magnetic	CoFe ₂ O ₄ nanofibers	ΔS _m ≈ 1.71 J/kg·K; ΔT _a d ~0.93 K; RCP ~7.6 J/kg	Good low-cost magnetocaloric material	[153]
	Ni _{0.5} Zn _{0.5} Fe ₂ O ₄	Tunable Curie temp: ~350–619 K	Ternary ferrite with optimized RCP	[154]
	ZnFe ₂ O ₄	ΔT _a d very low (~0.0024 K)	Not suitable for primary MCE but chemically stable	[155]

Coloring	ZnFe ₂ O ₄	L*: ~51.5 (yellow); band edge ~698 nm	Tuneable by annealing, stable in coatings	[156]
	CoFe ₂ O ₄	L*: ~33.5–36.7 (dark pigment)	High-temperature black ceramic pigment	[157]
	Zn _{1-x} Mg _x Fe ₂ O ₄	NIR reflectance >51%	Cool-coating pigment; reduces surface temp by ~16 °C	[158]
	MnFe ₂ O ₄	Black pigment; strong absorption	Industrially used; data on L* limited	[159]
Supercapacitor	MnFe ₂ O ₄ /MoS ₂	Capacitance: ~2093 F/g; energy: ~46.5 Wh/kg	Highest performance; great stability (~2000 cycles)	[160]
	Mn _{0.95} Zn _{0.05} Fe ₂ O ₄	Capacitance: ~829 F/g; energy: ~77.5 Wh/kg	High energy density; retains 80% after 8000 cycles	[135]
	NiFe ₂ O ₄ nanofibers	Capacitance: ~1130 F/g; energy: 34.7 Wh/kg	Long-term stability (~88% after 10,000 cycles)	[161]
	NiFe ₂ O ₄ /CNT composite	Capacitance: ~343 F/g; energy: ~23.4 Wh/kg	High power: ~467 W/kg; retains 89 % after 5000 cycles	[162]

5. TRANSITION METAL SUBSTITUTED METAL FERRITE NPS

Ferrites' chemical composition can be tuned by doping with transition metal ions such as Zn²⁺, Cu²⁺, Co²⁺, Mn²⁺, and Ni²⁺, thereby modifying their magnetic characteristics and enhancing performance in various applications [163, 164]. Such doping alters magnetic parameters—including remanence, coercivity, and susceptibility—by changing the magnetic moment and crystal structure, especially with divalent ions like Zn²⁺ [165, 166]. These modifications enable tailored properties for applications in biomedical fields, supercapacitors, and magnetic devices [166]. M. Shakil et al. [167] reported that in Zn_xCd_{0.375-x}Co_{0.625}Fe₂O₄ synthesized via co-precipitation, doping increases lattice parameters and affects characteristic bands (v1 and v2), influenced by sol-gel processing and calcination. Similarly, Akshay B. Kulkarni et al. [168] observed in Cd²⁺-substituted Co-Ni ferrites (20–24 nm, cubic spinel) that saturation magnetization decreased (52.74 to 32.68 emu·g⁻¹), coercivity first increased then declined, and remanence dropped (10.1 to 6.21 emu/g) with increasing Cd²⁺. M. Ounacer et al. [169] found that Al³⁺ substitution in cobalt ferrites (21–43.5 nm) reduced particle size and hyperfine field with increasing concentration, while M(T) curves indicated interparticle effects with TB shifting to higher temperatures.

6. FUTURE APPLICATIONS

It is evident that the future trend in applications for magnetic spinel ferrites will center on fine-tuning the particle size, shape, and crystallinity to manage the necessary magnetic characteristics by change of the synthetic processes. In addition to production and modification, doping is another useful technique for producing nonaggregate and monodisperse nanosized

spinel ferrites, which affects their physical and chemical properties. Magnetic spinel ferrites are effective magnetic materials that can be used to treat magnetic hyperthermia. The use of spinel ferrite-based materials to treat hyperthermia has been documented in numerous publications, however the field is still young and needs more research to address issues such as adjusting the size, shape, and magnetic characteristics of nanoparticles. Furthermore, one of the most crucial problems in obtaining magnetic ferrite nanoparticles with the desired performance for biomedical applications is the need to investigate more effectively effective ways of surface modification for spinel ferrites in the future. In order to develop the photocatalytic characteristics of spinel ferrite nanoparticles for the breakdown of organic pollutants, future studies must solve certain hurdles, even though the uses of magnetic spinel ferrites for wastewater treatment have expanded. The future of ferrite nanoparticle applications in supercapacitors is characterized by the development of doped ferrite nanocomposites, to enhance electronic conductivity and overall performance. Spinel ferrites like $\text{MnZnFe}_2\text{O}_4$ are promising due to their high energy density, durability, and good capacitance retention. External magnetic field influence is another area of investigation to potentially enhance electrochemical performance. Nanostructured materials, such as nanoneedles, are being explored to improve specific capacitance, long-term stability, and columbic efficiency. Researchers are also focusing on advanced materials and technologies for doping of different materials on metal ferrites.

7. CONCLUSIONS

This review highlights the remarkable progress made in the synthesis and applications of doped and undoped metal ferrite nanoparticles. Various synthesis techniques, including sol-gel, hydrothermal, co-precipitation, and microemulsion methods, have proven to be essential for fine-tuning the size, shape, and crystalline properties of ferrites. These precise modifications directly influence their structural, optical, and magnetic behaviors, which are critical for their performance in diverse applications.

Metal ferrites, such as CoFe_2O_4 , NiFe_2O_4 , and ZnFe_2O_4 , stand out for their stability, narrow bandgaps, and distinct magnetic properties. These features make them excellent candidates for a broad range of applications, including environmental remediation through photocatalysis, sensors for detecting pollutants, imaging technologies using photoluminescence, and energy storage devices like supercapacitors. By incorporating transition metals such as Zn^{2+} , Cu^{2+} , and Mn^{2+} , the properties of ferrites can be further enhanced to deliver greater efficiency and versatility.

The biomedical applications of ferrites also demonstrate their growing potential in healthcare. From targeted drug delivery to magnetic hyperthermia for cancer treatment and medical imaging, ferrite nanoparticles offer innovative solutions for modern medical challenges. Additionally, their role as efficient photocatalysts and high-performance energy storage materials positions them as key players in tackling environmental and energy-related issues. Metal ferrite nanoparticles, with their adaptable properties and diverse functionalities, hold significant promise for future technologies in energy, healthcare, and environmental fields. As research continues to improve synthesis techniques and material designs, these versatile materials are poised to make a meaningful impact in solving real-world challenges and advancing next-generation innovations.

Acknowledgments. The authors gratefully acknowledge the support and resources provided by Dr. B. N. P. Arts, Smt. S. G. G. Commerce and Smt. S. A. M. Science college, Lonavala MS, India. We extend our sincere thanks to Annasaheb Magar college, Hadapsar, MS, India for providing their research facilities.

CRedit authorship contribution statement. Tanuja Pandit, Vaibhav Kanke, Ganesh Tupe: Data curation, Writing – original draft. R. U. Mene, Amar S. Katkar: Writing – original draft, Writing – review & editing.

Declaration of competing interest. The authors state there is no conflict of interest.

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