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**Review**

# Advances in the Field of Ferrites Over the Last Decade: Synthesis, Properties, and Emerging Applications

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**Abstract:**
Ferrites, a structurally diverse family of iron-oxide-based magnetic ceramics, have experienced a remarkable renaissance over the past decade, driven by growing demands across energy technology, biomedicine, environmental remediation, and high-frequency electronics. This review surveys the major advances recorded between 2014 and 2024, covering developments in spinel, hexagonal, and garnet ferrite systems. We highlight breakthroughs in nanostructure engineering, cation substitution strategies, and green synthesis protocols, as well as their impact on electromagnetic wave absorption, lithium-ion battery anodes, photocatalytic degradation of organic pollutants, and targeted drug delivery. Emerging frontiers such as room-temperature multiferroic composites, magnonic devices, and machine-learning-guided compositional design are discussed. Together, these developments underscore that ferrite research remains one of the most fertile and practically consequential domains within the broader landscape of functional materials science.

**Keywords:** spinel ferrites, hexagonal ferrites, garnet ferrites, nanoferrites, electromagnetic wave absorption, photocatalysis, biomedical applications, multiferroics

## 1. Introduction

Ferrites constitute a broad class of iron-oxide-based compounds that have been exploited in magnetic applications since at least the mid-twentieth century. Their enduring relevance stems from a distinctive combination of properties, namely tunable saturation magnetisation, moderate electrical resistivity, chemical stability, and low production cost, that few competing material families can simultaneously offer. Yet, if the last ten years have demonstrated anything, it is that the story of ferrites is far from complete. The progressive miniaturisation of electronic devices, the urgent search for sustainable energy technologies, and the rapid growth of biomedical engineering have together posed new and stringent demands on magnetic materials, demands that have in turn catalysed a burst of innovative research into ferrite systems.

The family is conventionally subdivided according to crystal structure. Spinel ferrites (general formula $MFe_2O_4$, where M represents one or more divalent metal cations) are by far the most studied and commercially widespread, underpinning everything from transformer cores to magnetic resonance imaging contrast agents.[1] Hexagonal ferrites, particularly M-type barium and strontium hexaferrites, have long been the material of choice for permanent magnets and microwave absorbers, while yttrium iron garnet (YIG) and related garnet phases occupy a specialized niche in microwave and magnonic technologies.[2] Over the past decade, however, the boundaries between these sub-families have become increasingly permeable, with composite, graded, and heterojunction architectures blending properties from multiple structure types.

The objective of this review is not to be encyclopaedic, as several thousands of ferrite-related articles appear in the literature each year, but rather to identify and contextualise the themes and achievements that have most substantially advanced the field between 2014 and 2024. We draw primarily on peer-reviewed journal articles, but also note key reviews and book chapters where they provide essential background. The discussion is organised around structural families, with sections devoted to synthesis innovations, structure-property relationships, and application domains, before closing with a look at emerging directions and unresolved challenges.

## 2. Spinel Ferrites: Compositional and Nanostructural Engineering

Spinel ferrites retain their position at the centre of ferrite research, but the questions being asked of them have shifted considerably. Whereas earlier decades were largely preoccupied with bulk polycrystalline ceramics for transformer and inductor applications, the past ten years have seen the focus migrate towards nanoparticles, thin films, and heterostructures, motivated above all by biomedical and energy-related targets.

A particularly productive line of enquiry has concerned the precise engineering of cation distribution between the tetrahedral (A) and octahedral (B) sublattices of the spinel structure. It has been known for decades that the degree of inversion, that is, the fraction of $Fe^{3+}$ ions residing on A sites rather than B sites, profoundly influences magnetic ordering, but the ability to control inversion deliberately and reproducibly at the nanoscale has only recently become tractable. Carta and colleagues demonstrated that rapid thermal annealing of cobalt ferrite nanoparticles could systematically shift the inversion parameter from approximately 0.68 toward 1.0, yielding coercive fields that varied by almost an order of magnitude across the series.[3] Similar control has been achieved by varying the ratio of hydrazine to metal precursor in co-precipitation syntheses of nickel zinc ferrites, a finding with direct implications for the design of high-frequency inductors.[4]

Cation substitution with rare-earth elements has emerged as another major theme. The incorporation of small quantities of $La^{3+}$, $Gd^{3+}$, $Nd^{3+}$, or $Er^{3+}$ into spinel lattices has been shown to modify grain growth during sintering, suppress eddy current losses, and in several cases enhance saturation magnetisation by reducing antisite defect concentrations. A systematic study by Akhtar et al. on gadolinium-substituted cobalt ferrites reported a 12% improvement in magnetocrystalline anisotropy relative to the parent phase, attributed to single-ion anisotropy contributions from $Gd^{3+}$ occupying B sites.[5] These results have stimulated interest in designing ferrite phases that bridge conventional spinel behaviour and the strong anisotropy typical of hexagonal systems.

In the biomedical sphere, superparamagnetic iron oxide nanoparticles (SPIONs) based on magnetite ($Fe_3O_4$) and maghemite (gamma-$Fe_2O_3$) have continued to attract intense interest as MRI contrast agents, hyperthermia mediators, and drug carriers. However, a notable shift occurred around 2016 to 2018 when mixed-metal spinel nanoparticles, particularly Zn-, Mn-, and Co-doped variants, were shown to outperform pure magnetite in magnetic hyperthermia by virtue of their higher specific absorption rates (SAR) under radiofrequency fields.[6] Lee and coworkers reported a $Zn_{0.4}Fe_{2.6}O_4$ composition that achieved a SAR of approximately 432 W $g^{-1}$ at 500 kHz, several times higher than comparably sized magnetite particles, while maintaining biocompatibility in cell viability assays.[7] This observation has since been extended to ternary and quaternary spinel systems, where combinatorial optimisation of composition and particle size is now actively pursued.

Spinel ferrites have also found renewed relevance in energy storage. Several groups reported between 2018 and 2022 that nickel ferrite ($NiFe_2O_4$) and cobalt ferrite ($CoFe_2O_4$) nanoparticles deliver specific capacities exceeding 900 mAh $g^{-1}$ as anodes in lithium-ion cells, substantially above the theoretical capacity of graphite.[8] The conversion-type lithiation mechanism, whereby the ferrite is electrochemically reduced to metallic nanoparticles embedded in a $Li_2O$ matrix, was characterised in detail using operando X-ray diffraction and transmission electron microscopy, providing a mechanistic foundation for subsequent optimisation of cycling stability through carbon encapsulation and electrolyte engineering.[9]

## 3. Hexagonal Ferrites: Millimetre-Wave Absorption and Permanent Magnet Development

Hexagonal ferrites, particularly the M-type phases $BaFe_{12}O_{19}$ and $SrFe_{12}O_{19}$, are characterised by uniaxial magnetocrystalline anisotropy fields of around 14 to 17 kOe, making them effective microwave absorbers in the gigahertz range and viable alternatives to rare-earth-containing permanent magnets for certain applications. Both of these roles have seen significant development during the review period.

A key challenge in microwave absorption is achieving effective attenuation across a broad bandwidth with a thin absorber layer, a combination that is difficult to realise with a single-phase material. Research between 2015 and 2022 increasingly addressed this through composite architectures that combine hexaferrite with a dielectrically lossy phase, exploiting impedance matching conditions to enhance both reflection loss and bandwidth.[10] Studies by Che et al. showed that hybridising $BaFe_{12}O_{19}$ nanoplatelets with reduced graphene oxide yielded absorbers with a minimum reflection loss of 54 dB at 16.4 GHz and an effective absorption bandwidth of 6.1 GHz at a filler loading of 50 wt%.[11] Subsequent work has refined the understanding of impedance matching through transmission line modelling, and the principle of combining hard magnetic hexaferrite with a soft spinel phase in a core-shell geometry has been extended to produce exchange-spring absorbers with simultaneously improved magnetic loss and dielectric tunability.

On the permanent magnet front, the decade witnessed a concerted effort to enhance the energy product $(BH)_{max}$ of hexaferrite ceramics beyond the canonical ceiling of approximately 45 kJ $m^{-3}$. The substitution of $La^{3+}/Co^{2+}$ pairs for $Ba^{2+}/Fe^{3+}$ in the M-type lattice has been known to improve coercivity, but recent optimisation of sintering atmospheres and cooling protocols has allowed $(BH)_{max}$ values approaching 50 kJ $m^{-3}$ to be reliably reproduced.[12] While this still falls short of the rare-earth-free target set by the US Critical Materials Institute, it represents a meaningful advance for applications such as loudspeakers, DC motors, and magnetic bearings where the cost and supply-chain risks of rare-earth magnets are major concerns.

W-type, Y-type, and Z-type hexaferrites, which have historically received far less attention than the M-type phases, enjoyed a resurgence of interest during this period, particularly in connection with millimetre-wave (30 to 300 GHz) applications. The natural ferromagnetic resonance frequency of W-type hexaferrites lies in the range 50 to 70 GHz, making them intrinsically suited to absorber and circulator applications at frequencies relevant to 5G and automotive radar systems.[13] A number of research groups reported phase-pure synthesis of W-type and Z-type hexaferrites via sol-gel combustion and co-precipitation routes, with subsequent microwave characterisation confirming strong absorption near 60 GHz, a finding with direct relevance to frequency-selective surface design.[14]

## 4. Garnet Ferrites: Magnonic Devices and Low-Damping Films

Yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) occupies a singular position among magnetic insulators by virtue of its exceptionally low spin-wave damping parameter (Gilbert damping alpha approximately $10^{-4}$ to $10^{-5}$), a property that makes it the material of choice for microwave signal processing and, more recently, for the emerging field of magnonics, which uses spin waves as information carriers in lieu of electrical currents.[15]

The most transformative development in garnet ferrite research during the review period was the demonstration of the spin Seebeck effect (SSE) and spin pumping phenomena in YIG/normal-metal bilayers, which underpinned a new sub-discipline of spin caloritronics. Uchida and colleagues' foundational SSE measurements on YIG/Pt interfaces, published around 2010 but extended substantially in subsequent years, showed that a longitudinal thermal gradient in a YIG film generates a transverse spin current detectable via the inverse spin Hall effect.[16] This observation motivated an enormous body of follow-on work exploring how the spin-wave spectrum, and hence the SSE magnitude, could be tuned by film thickness, doping, and grain boundary engineering.

Thin-film deposition of YIG by pulsed laser deposition (PLD) and magnetron sputtering reached new levels of sophistication during this period. Several groups demonstrated epitaxial YIG films on gadolinium gallium garnet (GGG) substrates with room-temperature damping parameters below $1 \times 10^{-4}$, comparable to the best single-crystal bulk values.[17] Crucially, the ability to grow such films by sputtering, a scalable CMOS-compatible technique, rather than exclusively by PLD opened realistic pathways toward on-chip magnonic integrated circuits. Concurrent advances in patterning YIG into waveguide geometries using ion beam etching demonstrated spin-wave propagation over distances exceeding 1 mm at room temperature, with group velocities sufficient for practical signal processing applications.[18]

Bismuth-substituted YIG (Bi:YIG) gained renewed attention owing to its significantly enhanced Faraday rotation coefficient of approximately 8 degrees per micrometre, compared to 0.1 degrees per micrometre for undoped YIG, which makes it highly attractive for magneto-optical isolators in photonic integrated circuits. Achieving device-quality Bi:YIG films with both low optical loss and low magnetic damping proved challenging for much of the decade, but a 2021 study using liquid phase epitaxy on silicon-on-insulator substrates reported insertion losses below 2 dB together with isolation ratios above 30 dB, a combination close to the threshold for practical deployment in photonic chips.[19]

## 5. Advances in Synthesis and Characterisation

Across all structural families, this decade witnessed a substantial broadening of the synthetic toolkit available for preparing ferrite materials. Co-precipitation, solid-state reaction, and sol-gel methods remain widely employed, but several newer approaches have attracted growing interest due to their advantages in controlling particle size distributions, morphology, and compositional homogeneity.

Hydrothermal and solvothermal synthesis has matured considerably, with careful control of mineraliser concentration, precursor stoichiometry, and temperature ramp rate enabling the reproducible preparation of phase-pure nanoferrites with defined morphologies such as cubes, octahedra, nanorods, and hollow spheres, that were difficult to achieve reliably by aqueous co-precipitation.[20] The ability to tune particle shape is particularly significant because magnetisation reversal processes in nanoparticles depend strongly on geometry, meaning that morphological control provides an additional handle on coercivity and anisotropy beyond compositional substitution.

Green synthesis methodologies also advanced meaningfully. Plant-extract-mediated synthesis, in which polyphenols and other phytochemicals act simultaneously as reducing agents and capping ligands, was demonstrated for a range of spinel ferrite compositions using extracts from sources including aloe vera, hibiscus, and pomegranate peel.[21] Although the reproducibility of such methods across different extract batches has been questioned, several studies reported photocatalytic activities for plant-synthesised ferrite nanoparticles that matched or exceeded those of conventionally prepared materials, suggesting that the organic residues may serve a beneficial role as surface passivants or dopants rather than merely as synthetic auxiliaries.

On the characterisation front, the decade saw increased use of neutron powder diffraction for resolving cation distributions in spinel ferrites, a capability that X-ray diffraction alone cannot provide due to the near-identical scattering factors of Fe and many substituting cations at X-ray wavelengths. Synchrotron X-ray absorption spectroscopy (XANES and EXAFS) similarly became more routinely accessible, permitting oxidation-state and local-coordination analyses on nanogram quantities of material.[22] Electron magnetic circular dichroism (EMCD) in the transmission electron microscope enabled element-specific magnetic mapping at nanometre resolution, a technique that proved particularly valuable for characterising exchange coupling at core-shell interfaces.[23]

## 6. Emerging Application Domains

The application landscape for ferrites has diversified substantially over the review period, reflecting both the broadening of the compositional and morphological palette available and the emergence of new technological challenges.

In environmental remediation, heterogeneous Fenton-like photocatalysis using spinel ferrite nanoparticles emerged as a promising strategy for degrading persistent organic pollutants such as tetracycline, bisphenol A, and various synthetic dyes under visible-light irradiation.[24] The visible-light activity arises from the relatively narrow bandgaps of many ferrites (1.9 to 2.3 eV), which allow direct photoexcitation under solar-spectrum radiation. Coupling ferrite photocatalysts with persulfate or $H_2O_2$ as co-oxidants dramatically accelerates pollutant mineralisation, and the magnetic separability of ferrite particles, a practical advantage absent in $TiO_2$ or ZnO, allows catalyst recovery by applied field rather than centrifugation.[25] Reported pseudo-first-order rate constants for tetracycline degradation over $MnFe_2O_4$

composites exceed 0.1 min$^{-1}$, comparable to the best reported values for non-magnetic visible-light photocatalysts.[26]

In the domain of electromagnetic compatibility, the increasing density of wireless communications from 4G/LTE through to 5G and Wi-Fi 6 has placed growing pressure on materials capable of attenuating electromagnetic interference (EMI) across broad frequency ranges. Ferrite-based polymer composites, in which spinel or hexaferrite nanoparticles are dispersed in polyurethane, silicone, or epoxy matrices, have been extensively characterised for this application during the review period.[27] Beyond simple fillers, core-shell particles combining a magnetically hard hexaferrite core with a magnetically soft spinel shell were shown to exhibit dual magnetic loss mechanisms, namely natural resonance loss from the hard core and eddy current loss from the soft shell, yielding broader absorption bandwidths than either phase alone.[28]

Ferrite-based multiferroic composites, in which ferrite grains are coupled to ferroelectric phases such as $BaTiO_3$ or $Pb(Zr,Ti)O_3$, attracted sustained interest throughout this decade as candidates for voltage-tunable microwave devices, magnetoelectric sensors, and potentially four-state memory cells.[29] Magnetoelectric coupling coefficients exceeding 100 mV cm$^{-1}$ Oe$^{-1}$ have been reported for layered $CoFe_2O_4/BaTiO_3$ laminates, a value sufficient to be detectable in practical sensor geometries.[30]

## 7. Machine Learning and Computational Approaches

One of the most noteworthy methodological shifts of the past decade has been the integration of machine learning (ML) and high-throughput computational screening into ferrite research. Density functional theory (DFT) calculations have long been employed to evaluate formation energies, electronic structures, and magnetic exchange interactions in ferrites, but the construction of large computational datasets during this period, notably those hosted on the Materials Project and AFLOW repositories, has made it possible to apply ML regression models to predict properties such as saturation magnetisation, Curie temperature, and anisotropy constant for unexplored compositions.[31]

A 2022 study by Nelson and colleagues trained a gradient-boosted regression model on a dataset of approximately 2,400 spinel-structure compounds to predict saturation magnetisation and band gap, achieving cross-validated mean absolute errors of approximately 10 emu g$^{-1}$ and 0.3 eV respectively.[32] More ambitious efforts have employed generative adversarial networks to propose novel ferrite compositions with targeted property profiles, an approach that has yielded several experimentally synthesised materials with properties superior to those predicted by simple linear interpolation between known end-members.[33]

Parallel advances in micromagnetic simulation, including GPU-accelerated implementations of the Landau-Lifshitz-Gilbert equation with sub-nanometre mesh resolution, have enabled quantitative comparison of simulated and measured hysteresis loops for complex nanostructures including core-shell particles, nanorings, and patterned thin-film elements.[34] These tools have proven especially valuable for interpreting the switching behaviour of exchange-biased ferrite nanostructures, where the interfacial spin configuration is inaccessible by bulk characterisation techniques.

## 8. Future Perspectives and Unresolved Challenges

Despite the remarkable progress surveyed above, several significant challenges remain unresolved and are likely to define the next phase of ferrite research. From a fundamental standpoint, the microscopic origin of magnetic relaxation in cation-substituted garnets and the nature of spin freezing at the surfaces of ferrite nanoparticles below approximately 5 nm remain subjects of active debate. Resolving these questions will require a combination of ultrahigh-resolution electron microscopy, polarised neutron scattering, and advanced DFT+U or hybrid functional calculations that go beyond current standard approaches.

From an applications perspective, the integration of ferrite thin films with photonic and phononic platforms represents one of the most technically demanding frontiers. Achieving low-loss, wafer-scale YIG films on silicon remains elusive because of the significant lattice and thermal expansion mismatch between YIG and Si, and the strong sensitivity of magnetic damping to interfacial chemistry. The development of interlayer buffer strategies, analogous to those employed in III-V epitaxy, offers a plausible route forward, but progress to date has been incremental.[35]

The growing recognition that ferrite nanoparticle toxicity is a function not just of core composition but also of surface chemistry, agglomeration state, and particle corona has begun to reshape the biomedical ferrite research agenda. Regulatory pathways for clinical translation of new ferrite formulations are laborious, and the field would benefit from more systematic in vivo biodistribution studies that track particle fate across tissue types and time scales extending beyond the week-long windows typically reported.[36]

Finally, the environmental sustainability of ferrite production deserves greater attention than it has historically received. While ferrite raw materials are broadly Earth-abundant, the calcination and sintering steps in ceramic processing are energy-intensive, and the solvents employed in wet-chemical nanoparticle synthesis frequently include ethylene glycol, oleylamine, and other compounds with non-trivial environmental footprints. Life-cycle assessment of competing synthesis routes, integrated with techno-economic analysis, would provide a rational basis for prioritising greener manufacturing strategies without sacrificing product quality.

## 9. Conclusions

The past decade has confirmed that ferrite materials science is a field not merely sustaining its historical relevance but actively expanding into new scientific and technological territory. Nanostructure engineering and cation substitution have unlocked magnetic properties unattainable in bulk ceramics. New synthesis protocols, from hydrothermal routes to plant-mediated green chemistry, have broadened access to morphologically controlled nanomaterials. In the application domain, ferrites now play meaningful roles in energy storage, environmental remediation, and clinical medicine, supplementing their long-established positions in magnetics and microwave engineering. The integration of machine learning into compositional design and the rise of magnonic device research signal that ferrite science is entering a more data-driven, computationally guided phase. Addressing the remaining challenges around interfacial physics, clinical translation, and sustainable manufacturing will require sustained interdisciplinary collaboration, but the trajectory of the field over the last ten years provides ample reason for confidence.

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