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Review Article

Recent Advances in Nickel Ferrite-Polymer Nanocomposites for Radar Absorbing Material Applications

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Abstract— Nickel ferrite ($NiFe_2O_4$) and its polymer-based composites have emerged as promising candidates for radar absorbing materials (RAMs) due to their unique combination of magnetic and dielectric loss mechanisms. This review highlights recent advances in synthesis strategies, including sol–gel, hydrothermal, co-precipitation, and microwave-assisted methods, which enable precise control of particle size, morphology, and crystallographic defects. Such control supports flexible structural design of nickel ferrite spinel structures, allowing dopant incorporation to tailor magnetic anisotropy and saturation magnetization. These structural features directly affect electromagnetic performance. Magnetic loss is mainly governed by natural resonance and, to a lesser extent, eddy current effects, while dielectric loss arises from dipole polarization, interfacial polarization, and conduction loss. The synergistic balance of magnetic and dielectric losses makes nickel ferrite–polymer nanocomposites promising broadband radar absorbing materials. The discussion emphasizes the role of cation substitution, polymer matrices, and hybridization with carbon-based materials in enhancing microwave absorption bandwidth and impedance matching. Various synthesis approaches, including sol–gel, hydrothermal, and in-situ polymerization, are compared with respect to their influence on particle size, morphology, and absorption efficiency. Challenges such as limited bandwidth, thermal and mechanical stability, and scalability are highlighted, along with potential solutions through advanced nanostructuring, multifunctional design, and sustainable synthesis. Future research directions are also outlined to support the development of next-generation stealth and electromagnetic interference shielding technologies.

Keywords— *Composites; Nickel ferrite; Polymer; Radar absorbing material.*

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1. INTRODUCTION

The rapid advancement of electronic and communication technologies in the past few decades has brought remarkable improvements in information processing, wireless communications, defense systems, and consumer electronics [1]. At the same time, the widespread utilization of high-frequency devices has created an inevitable challenge: the generation of unwanted electromagnetic (EM) radiation[2]. These emissions can propagate through free space or conductive pathways, causing electromagnetic interference (EMI), which may disrupt the proper functioning of sensitive electronics, degrade communication signals, and even pose risks to human health when exposure exceeds permissible levels [2]. Addressing these concerns has led to the accelerated development of advanced electromagnetic wave (EMW) management materials. Among the most intensively explored candidates are radar absorbing materials (RAMs) for stealth and defense applications, and EMI shielding materials for commercial and industrial electronics.

Within this landscape, ferrite-based materials have emerged as highly promising due to their favorable balance of magnetic loss and dielectric loss mechanisms [3]. Nickel ferrite, a member of the spinel ferrite family, exhibits tunable electrical conductivity, high chemical stability, and strong magnetic properties that can be tailored by composition, particle size, and synthesis method [4]. These attributes allow nickel ferrite to interact with electromagnetic waves in the gigahertz frequency range, making it an attractive choice for both stealth technologies and shielding applications. When combined with conductive polymers, carbonaceous frameworks, or hybrid nanostructures,

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nickel ferrite composites display enhanced absorption bandwidths, lightweight design, and structural flexibility—features essential for modern defense systems and portable electronic devices.

Electromagnetic interference has become a critical issue in modern society [5]. The proliferation of 5G networks[6],satellite communications, radar systems [7], Internet-of-Things (IoT) devices [8], and high-speed microprocessors has intensified the density of electromagnetic radiation across wide frequency bands [9]. Sensitive medical equipment [10], avionics [11], and military radar systems are especially vulnerable to EMI-induced malfunctions, which can lead to catastrophic consequences. Traditional metallic shielding materials, such as copper or aluminum, offer high electrical conductivity and thus efficient reflection of EM waves [12]. However, metals are heavy, prone to corrosion, and often limited in terms of absorption-dominated shielding[13]. In many cases, reflective shielding only redirects interference rather than dissipating it, which can lead to secondary EMI pollution.

To overcome these shortcomings, research has shifted toward lightweight, corrosion-resistant, and absorption-dominated materials that not only block but also attenuate electromagnetic waves (Lu). The ideal EMI shielding material should possess a balance of high electrical conductivity, magnetic permeability, dielectric polarization capability, and mechanical flexibility [14]. Hybrid composites, especially those integrating ferrites with conductive or dielectric matrices, are increasingly seen as a pathway to achieving this balance [15]. Nickel ferrite, owing to its high resistivity compared with metallic fillers, reduces eddy current losses while still offering magnetic loss contributions[16]. When incorporated into polymeric or carbon-based systems, it provides synergistic effects that enable superior EMI shielding effectiveness across broad frequency ranges [17].

In defense technology, stealth remains one of the highest priorities for next-generation aircraft, ships, and ground vehicles. Stealth platforms rely heavily on radar absorbing materials to minimize their radar cross section (RCS), thereby reducing the probability of detection by enemy radar [18]. The effectiveness of a RAM is determined not only by its ability to attenuate incident radar waves but also by its lightweight nature, mechanical durability, and stability under harsh conditions. Conventional RAMs, such as carbon-based coatings and metal flakes, often suffer from narrow absorption bandwidths or poor mechanical integrity [19].

Nickel ferrite provides unique advantages as a RAM constituent. The combination of natural resonance, exchange resonance, and conduction losses leads to efficient absorption of electromagnetic waves in the microwave range. Moreover, the spinel structure of nickel ferrite can accommodate a variety of dopant ions (e.g., Zn^{2+}, Co^{2+}, Mn^{2+}), which tune its magnetic anisotropy and saturation magnetization, thereby shifting absorption peaks and broadening effective bandwidths [20]. These tunable properties make nickel ferrite composites particularly attractive for multi-band and broadband radar absorption applications. When dispersed within polymer matrices such as polyaniline (PANI), polypyrrole (PPy), or polyvinylidene fluoride (PVDF), nickel ferrite nanoparticles can deliver high-performance, flexible, and lightweight absorbing coatings suitable for stealth technologies.

The performance of nickel ferrite-based composites in both EMI shielding and RAMs is intimately tied to their structural and microstructural characteristics. Parameters such as particle size, morphology, crystallinity, and distribution within the host matrix dictate the pathways of EM wave attenuation. For instance, nanoscale ferrite particles exhibit large surface areas and numerous interfacial regions, which facilitate interfacial polarization and enhance dielectric losses [21]. Similarly, controlled synthesis methods, such as sol–gel, hydrothermal, co-precipitation, and microwave-assisted techniques, provide opportunities to tailor particle size distribution and crystallographic defects, directly influencing magnetic resonance behavior [22].

The choice of polymer matrix is equally important. Conductive polymers like polyaniline and polypyrrole introduce charge carrier hopping and polaron/bipolaron transport mechanisms, contributing to electrical conductivity and dielectric losses [1]. On the other hand, insulating matrices such as PVDF offer mechanical flexibility and processability, though they may require additional conductive fillers to optimize absorption. Hybrid strategies, where nickel ferrite nanoparticles are combined with carbon nanotubes, graphene, or MXenes, further enhance conductivity and interfacial polarization, leading to outstanding performance in both EMI shielding and radar absorption.

Despite remarkable progress, several challenges remain in the practical deployment of nickel ferrite-based composites. One of the primary limitations is the trade-off between absorption performance and material thickness. Achieving high absorption at lower thicknesses remains a critical design goal, particularly for applications where weight and size constraints are stringent [23]. Additionally, large-scale synthesis of uniform, defect-controlled ferrite nanoparticles at low cost is an ongoing challenge. The compatibility of ferrite fillers with polymer matrices also requires careful surface modification to ensure homogeneous dispersion and long-term stability.

Looking forward, future research should emphasize multi-functional materials that combine EMI shielding and radar absorption capabilities with additional properties such as thermal management, mechanical robustness, and environmental stability. Advances in nanostructuring, 3D printing, and machine learning-assisted material design hold significant promise for accelerating the discovery of optimized ferrite-based composites [24]. Moreover, integrating sustainability considerations—such as green synthesis methods and recyclable polymer matrices—will be essential for aligning with global trends in eco-friendly material development.

This review aims to consolidate recent advancements in nickel ferrite-polymer with a dual emphasis on radar absorbing materials and electromagnetic interference shielding applications. The discussion will highlight the structure–property relationships that govern EM wave absorption, including the role of dopants, synthesis techniques, and composite architectures. Special attention will be given to polymer matrices, conductive hybrids, and emerging fabrication methods that enable superior performance. Finally, the review will outline current challenges and potential research directions toward next-generation multifunctional materials capable of meeting the stringent demands of both defense and civilian applications.

2. NICKEL FERRITE FUNDAMENTALS AND DOPING EFFECTS

Ferrites are known for their high saturation magnetization, high curie temperature, high permeability and low electrical conductivity, which aid to reduce eddy currents and energy loss [25]. Ferrites offer high working frequency, wide frequency band, and small coating thickness, making them suitable for microwave absorption applications, making them a popular choice among soft ferrites. These qualities make nickel ferrite extremely effective at suppressing electromagnetic radiation, particularly in the microwave area [26]. Ferrites absorb electromagnetic radiation primarily through magnetic losses such as natural resonance, domain wall motion, hysteresis loss and eddy currents, which enable the material to disperse radar signals [27]. The electrical, magnetic and catalytic properties of ferrites can be tuned by substitution of different cations such as Zn, Cu, Ni, Sr, Cd, and others in the metal sites [28]. This makes nickel ferrite an appealing choice for stealth technologies and RCS reduction in radar absorbing applications.

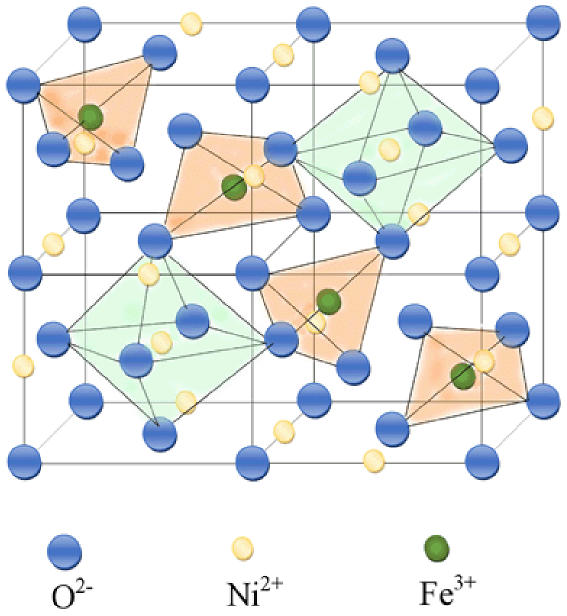

Figure 4. Schematic structure for nickel ferrite $NiFe_2O_4$ [29]

Nickel ferrite ($NiFe_2O_4$), an inverse spinel ferrite, has been widely explored for wide range of application especially its radar-absorbing features due to its rare combination of magnetic and dielectric characteristics with good chemical stability [4]. As seen in Figure 2.2 below, the trivalent cations are dispersed throughout tetrahedral and octahedral sites in inverse spinels, whereas the divalent cations reside in octahedral sites. Nickel ferrites are classified as soft ferrites because of their low coercivity, mild saturation magnetization, and minimal hysteresis losses. They also have other advantageous characteristics, including mechanical hardness, electrochemical stability, low dielectric and eddy current losses, good permeability at high frequencies, and fair price.

2.1. Magnetic and Dielectric Properties

The microwave absorption efficiency of a material is closely related to its magnetic and dielectric losses. Nickel ferrite ($NiFe_2O_4$), a well-known soft magnetic material, exhibits relatively high magnetic loss primarily due to natural ferromagnetic resonance and domain wall resonance [30]. These magnetic loss mechanisms contribute significantly to the attenuation of electromagnetic waves, making $NiFe_2O_4$ a promising candidate for microwave absorbing applications.

The magnetic properties of nickel ferrite are governed by a balance of exchange interactions, anisotropy, and microstructural features. These properties are crucial for magnetic loss mechanisms, which include natural resonance, domain wall resonance, and eddy current loss.

Saturation Magnetization (Ms). Bulk nickel ferrite typically exhibits saturation magnetization values around 50–55 emu/g [29], [31]. However, nanoscale particles often show reduced Ms due to spin canting, surface disorder, and finite-size effects [32]. Tailoring Ms is important because higher magnetization generally enhances magnetic permeability, thereby improving impedance matching and absorption performance in RAMs.

Coercivity (Hc). $NiFe_2O_4$ is a soft magnetic material with relatively low coercivity (<200 Oe in bulk form). Low coercivity facilitates rapid magnetization reversal under alternating electromagnetic fields, contributing to efficient magnetic losses. At the nanoscale, however, coercivity may increase due to single-domain behavior and surface anisotropy, offering tunability for specific frequency bands [33].

Magnetic Permeability (μ). The real (μ′) and imaginary (μ″) components of complex permeability describe the material's ability to store and dissipate magnetic energy, respectively. $NiFe_2O_4$ exhibits high permeability at low frequencies, which decreases at microwave frequencies due to relaxation phenomena. The imaginary component (μ″) corresponds to magnetic loss, primarily arising from natural resonance and domain wall motion. Controlling particle size, morphology, and doping can shift resonance frequencies to align with desired radar or EMI shielding applications [34].

However, its dielectric loss is typically moderate, which may limit its overall absorption performance, particularly in the GHz frequency range [1]. To address this, various strategies have been explored to enhance dielectric polarization, such as introducing defects, interfaces, or combining $NiFe_2O_4$ with dielectric or conductive components in composite structures. The addition of secondary phases can improve interfacial polarization and Maxwell–Wagner relaxation effects, thereby increasing the dielectric loss and tuning the impedance matching for more effective microwave absorption.

Electron Hopping Mechanism. A key feature of $NiFe_2O_4$ is the presence of mixed-valence Fe^{2+}/Fe^{3+} ions at octahedral sites [35]. Electron hopping between these ions under an alternating electric field contributes to dielectric polarization [36]. Similarly, Ni^{2+}/Ni^{3+} ions may also participate in hopping, depending on synthesis conditions and stoichiometry. This hopping mechanism enhances dielectric loss (ε''), leading to improved absorption.

Maxwell–Wagner Interfacial Polarization. The heterogeneous nature of nickel ferrite composites, particularly when embedded in polymers or hybridized with carbon nanostructures, gives rise to interfacial polarization at the boundaries between conducting and insulating regions. Under microwave irradiation, accumulated charges at interfaces induce strong polarization losses, contributing to attenuation [37].

Dielectric Constant and Frequency Dependence. Nickel ferrite typically exhibits a high dielectric constant at low frequencies, which decreases with increasing frequency due to the inability of dipoles to follow rapid oscillations. This frequency-dependent behavior is consistent with Maxwell–Wagner theory and Koop's phenomenological model. At microwave frequencies, dielectric relaxation and interfacial effects dominate, enhancing loss tangents crucial for RAM and EMI shielding applications.

2.2. Effect of Substitutions

Nickel ferrite crystallizes in an inverse spinel structure with the general formula $(Fe^{3+})[Ni^{2+}Fe^{3+}]O_4$, where parentheses denote tetrahedral (A) sites and brackets denote octahedral (B) sites. In this arrangement, Ni^{2+} ions preferentially occupy B-sites, while Fe^{3+} ions distribute between both A and B sites [38]. This cation distribution strongly influences the magnetic interactions due to superexchange coupling between metal ions via oxygen anions. Specifically, the antiferromagnetic A–B interaction between $Fe^{3+}(A)–O^{2-}–Fe^{3+}(B)$ and $Fe^{3+}(A)–O^{2-}–Ni^{2+}(B)$ dominates the magnetic behavior. The degree of inversion, defined as the fraction of divalent ions occupying B-sites, can be tuned by synthesis methods, thermal treatment, or doping, leading to variations in magnetic moment and dielectric polarization behavior.

Zn^{2+}: As a non-magnetic ion, Zn^{2+} tends to occupy the tetrahedral (A) sites in the spinel structure, displacing Fe^{3+} ions to the octahedral (B) sites [30], [39]. This redistribution enhances the superexchange interactions between B-site ions, leading to an increase in saturation magnetization. Moreover, Zn substitution improves impedance matching by reducing the permittivity–permeability mismatch, which is beneficial for microwave absorption.

Co^{2+}, Mn^{2+}, Cu^{2+}: These magnetic ions can replace Ni^{2+} in the octahedral sites, altering the magnetic anisotropy, coercivity, and magnetocrystalline properties of the ferrite. For instance, Co^{2+} enhances anisotropy and coercivity due to its strong spin–orbit coupling [31], while Mn^{2+} and Cu^{2+} influence the domain dynamics and spin canting, thereby modifying the overall magnetic loss behavior.

Zr^{4+}, Ti^{4+}, Al^{3+}: These non-magnetic, high-valence ions typically substitute Fe^{3+} at the octahedral sites, affecting the charge distribution and introducing lattice distortions [40]. Their substitution tends to influence dielectric behavior more prominently, leading to increased dielectric loss due to enhanced polarization mechanisms and defect formation. Additionally, such substitutions can reduce electrical conductivity and promote interfacial polarization, both of which are favorable for improving the microwave absorption capacity of $NiFe_2O_4$-based materials.

Through controlled substitution, it is possible to fine-tune the electromagnetic parameters of $NiFe_2O_4$, optimizing its performance as a radar absorbing material (RAM) across a wide frequency range.

3. POLYMER MATRICES AND COMPOSITE FORMATION

The integration of conductive polymers into nickel ferrite-based composites significantly enhances dielectric loss and impedance matching—two critical parameters that determine the performance of microwave absorbing materials (RAMs). Conductive polymers not only contribute to mechanical flexibility, which is essential for practical applications, but also promote key absorption mechanisms such as interfacial polarization and relaxation [41]. These mechanisms are vital in facilitating the effective attenuation of incident electromagnetic waves. **Table 1** summarizes the main characteristics, advantages, and limitations of various polymer matrices commonly used in ferrite-based radar absorbing material composites.

3.1. Polypyrrole

Polypyrrole (PPy) (**Figure 2**) is one of the most widely employed conductive polymers in the development of microwave absorbing composites [42]. Its popularity stems from its high electrical conductivity, low density, and ease of synthesis via in-situ polymerization. When combined with ferrite nanoparticles, the resulting composites exhibit synergistic effects—magnetic loss originating from the ferrite phase and dielectric loss from the PPy phase. This combination leads to enhanced microwave absorption performance across a broad frequency range. Moreover, the microstructure of PPy can increase the active surface area, thereby amplifying interactions with incident electromagnetic waves and facilitating multiple scattering and attenuation pathways.

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Table 1. Advantages and disadvantages of various polimer matrices

Polymer Matrix	Advantages	Disadvantages
Polypyrrole (PPy)	High electrical conductivity; strong dielectric loss contribution; easy in-situ polymerization; synergistic interaction with ferrites.	Limited mechanical strength; environmental stability can be an issue without proper modification.
Polyaniline (PANi)	Conductivity tunable via doping and pH; effective interfacial polarization; good synergy with magnetic fillers.	Processing complexity; conductivity sensitive to environmental conditions.
Polyvinylidene fluoride (PVDF)	Excellent flexibility, thermal stability, and mechanical strength; suitable for flexible and layered RAM structures.	Low intrinsic electrical conductivity; limited dielectric loss without conductive or magnetic fillers.
Mechanical milling (High-Polyvinyl chloride (PVC)	Good chemical resistance; low cost; easy processing.	Poor dielectric loss performance; requires fillers to achieve effective microwave absorption.

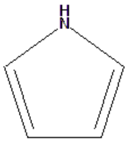

Figure 2. Chemical structure of polypyrrole monomer

3.2. Polyaniline

Polyaniline (PANi) is another extensively studied conductive polymer, known for its tunable electrical conductivity, which can be adjusted through doping levels and pH conditions during synthesis [43]. PANi can form percolative networks with ferrite particles, enabling efficient interfacial polarization and Maxwell–Wagner relaxation—two dominant mechanisms for dielectric loss at microwave frequencies. The ability of PANi to interact synergistically with the magnetic ferrite phase makes it an excellent candidate for designing high-performance RAM composites, offering a balanced contribution from both magnetic and dielectric components. Monomer of PANi can be seen in **Figure 3**.

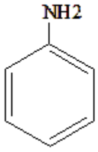

Figure 3. Chemical structure of polyaniline monomer

3.3. PVDF, PVC, and Other Polymers

Dielectric polymers such as polyvinylidene fluoride (PVDF) and polyvinyl chloride (PVC) are frequently employed as matrices in layered structures. PVDF, in particular, is favored for its excellent mechanical strength, thermal stability, and flexibility, which make it suitable for applications involving complex or flexible architectures [43]. However, due to its inherently low electrical conductivity, the dielectric loss of PVDF-based composites is relatively limited. To overcome this, magnetic fillers such as ferrites or conductive additives are introduced to improve impedance matching and enhance dielectric losses. This approach allows the composite to maintain desirable mechanical properties while achieving better electromagnetic absorption performance.

Table 2. Summary of nickel ferrite and polymer-based composites

Material	Formation Method	Effect on Properties	Refs
$NiFe_2O_4$/PANI	Mechanical Mixing	• Strong microwave absorption in X-band. • Enhanced EMI shielding through synergistic dielectric (PANI) and magnetic ($NiFe_2O_4$) losses.	[44]
Epoxy/Graphene/ $NiFe_2O_4$	Mechanical mixing	• Improved dielectric and magnetic loss. • Increased EMI shielding effectiveness. • Improved structural stability.	[45]
$NiFe_2O_4$/RGO	In-situ polymerization	• Enhanced electrical conductivity. • High EMI shielding effectiveness.	[46]
$Ni_{0.5}Zn_{0.5}Fe_2O_4$/Ppy	Mechanical Mixing	• Increased dielectric constant and AC conductivity with higher PPy content. • Strong interfacial polarization and reduced eddy current losses.	[47]
$Ni_{0.6}Cd_{0.4}Fe_2O_4$/Ppy	In-situ polymerization	• Improved thermal stability and ferromagnetism. • Strong EMI shielding in X-band. • Enhanced interfacial polarization and dielectric/magnetic losses.	[48]
$Ni_{0.32}Zn_{0.68}Fe_2O_4$/PVA	Hot pressing	• Strong microwave absorption in 2–5 GHz. • Dominant magnetic loss.	[49]
$NiFe_2O_4$/Polystyrene	Hot pressing	• Low temperature processing • Economica and scalable • Uniform particle size	[50]

3.4. Composite Formation

The fabrication technique plays a pivotal role in determining the dispersion, interfacial interaction, and overall performance of nickel ferrite–polymer composites. Several methods have been employed to integrate ferrite nanoparticles into polymer matrices, each offering distinct advantages and limitations. In-situ polymerization is one of the most widely used approaches, in which ferrite particles are incorporated during the polymerization process, leading to strong interfacial bonding and the formation of core–shell or homogeneous composite structures.

Solution casting or blending methods involve dispersing ferrite nanoparticles in a polymer solution, followed by solvent evaporation, which provides simplicity and versatility, although nanoparticle agglomeration can be an issue. For thermoplastic matrices such as PVDF or PVC, melt mixing or extrusion offers a scalable route to achieve good filler dispersion and mechanical stability, albeit at the cost of possible thermal degradation of the polymer [43].

Advanced strategies, including electrospinning and coating, enable the preparation of thin films or fibrous architectures with large surface areas, thereby enhancing interfacial polarization and microwave absorption. Additionally, layer-by-layer assembly provides precise control over composite architectures, facilitating gradient impedance matching and improved absorption bandwidth. These diverse fabrication routes strongly influence the microstructure of the resulting composites, which in turn governs their dielectric and magnetic losses, ultimately dictating the efficiency of radar wave attenuation. **Table 2** summarizes different formation methods of $NiFe_2O_4$-based materials and their general effects on properties reported in the literature.

4. MICROWAVE ABSORPTION MECHANISMS

Radar Absorbing Materials (RAM) are functional materials specifically engineered to attenuate incident electromagnetic waves—particularly in the microwave frequency range—by converting them into other forms of energy, most commonly heat [51], [52]. The efficiency of RAMs depends on a complex interplay between their structural, magnetic, and dielectric properties and the nature of the incident wave. The key mechanisms that contribute synergistically to microwave absorption include magnetic loss, dielectric loss, impedance matching, and performance evaluation through reflection loss (RL). As summarized in **Table 3**, the contributions of magnetic and dielectric losses complement each other in broadening the absorption bandwidth and enhancing the absorption efficiency of ferrite-based radar absorbing materials.

4.1. Magnetic Loss Mechanisms

Magnetic loss is a dominant absorption mechanism in ferrite-based RAMs, where the magnetic component of the electromagnetic wave interacts with the magnetic moments within the material. The principal magnetic loss mechanisms include:

Natural Resonance. This occurs when the frequency of the incoming microwave aligns with the intrinsic precessional frequency of the magnetic spins within the material. At this resonance condition, the system efficiently absorbs microwave energy, converting it into thermal energy through spin relaxation processes, also known as gyromagnetic resonance [53]. The natural resonance frequency is highly influenced by the material's crystal structure and particle size. For instance, smaller nanoparticles often exhibit higher resonance frequencies due to surface anisotropy effects [54]. By precisely controlling the particle size of nickel ferrite, it's possible to tune the maximum absorption frequency, making it an effective strategy for designing broadband RAMs.

Table 3. Contributions of magnetic and dielectric losses

Type	Mechanism	Factor	Contribution
Magnetic Loss	Natural resonance	Particle size, crystal structure, magnetic anisotropy	Dominant magnetic loss mechanism; tunable absorption peak and bandwidth through nanoparticle size control
Magnetic Loss	Domain wall resonance	Domain structure, grain size, magnetic softness	Minor contribution in nanoscale $NiFe_2O_4$ due to reduced multi-domain behavior
Magnetic Loss	Eddy current loss	Electrical resistivity, conductivity of fillers, skin depth.	Significant in composites containing conductive polymers or carbon-based additives
Dielectric Loss	Dipole polarization	Polar functional groups, defect density, polymer–ferrite interaction	Enhances dielectric loss through dipole relaxation processes
Dielectric Loss	Interfacial polarization (Maxwell–Wagner)	Interfacial area, conductivity contrast, nanoparticle dispersion.	Key contributor to broadband absorption in nanocomposites
Dielectric Loss	Conduction loss	Filler loading, percolation network, electrical conductivity	Improves absorption efficiency but requires optimization to avoid impedance mismatch

Domain Wall Resonance. In multi-domain magnetic materials, magnetic domains are separated by domain walls. When exposed to an alternating magnetic field, these domain walls oscillate or shift, dissipating energy as heat due to internal friction. This mechanism is dominant at lower frequencies (typically below 1 GHz) and becomes less significant at higher frequencies as the domain walls struggle to keep up with the rapid field reversal [55]. For nickel ferrite nanoparticles, which are often soft magnetic at the nanoscale, the contribution from domain wall resonance is minimal, making natural resonance the more critical magnetic loss mechanism in these materials.

Eddy Current Loss. Alternating magnetic fields induce circulating currents within conductive materials [56]. These currents experience electrical resistance, leading to Joule heating and energy dissipation. While ferrites are semiconductors with high electrical resistivity, eddy current loss can still be a significant factor in composites containing conductive polymers or carbon-based fillers. The magnitude of this loss is described by the skin effect theory, where at higher frequencies, currents are limited to a thinner surface layer, which can either increase or decrease the overall energy dissipation. By controlling the resistivity of the composite, eddy current loss can be fine-tuned to achieve an optimal balance between conduction and absorption.

4.2. Dielectric Loss Mechanisms

In addition to magnetic interactions, EM waves also interact with electric charges and dipoles in materials, leading to dielectric loss. This mechanism is crucial in $NiFe_2O_4$-polymer nanocomposites, as the polymer matrix enhances its contribution. Major dielectric loss mechanisms include:

Dipole Polarization. Molecules or functional groups with permanent or induced dipole moments attempt to align with the oscillating electric field of the microwave. This alignment process, especially at gigahertz frequencies, causes frictional energy loss due to the lag in response time, which generates heat. In composites, polar groups within the polymer matrix (e.g., –OH, –NH) or defects created during synthesis can act as effective dipole relaxation centers [57]. The interaction between the polymer and ferrite nanoparticles can also create new dipoles, further enhancing polarization and, consequently, dielectric loss.

Interfacial Polarization (Maxwell–Wagner Polarization). This occurs at interfaces between phases with differing electrical conductivities, such as between semiconducting ferrite particles and an insulating polymer matrix [58]. The accumulation of space charges at these interfaces generates localized electric fields, which in turn enhances microwave energy absorption. The large surface area of the nanoparticles in a nanocomposite provides numerous interfaces for this mechanism to occur, making it a key contributor to broadband absorption. The synergy between dielectric polarization and magnetic loss at these interfaces is essential for achieving superior RAM performance.

Conduction Loss. Materials that are semiconductors or weak conductors, like conductive polymers (e.g., PPy or PANi), allow for the flow of electrical charge. The movement of these charges causes energy to be dissipated as heat due to resistance. In nanocomposites, the formation of a percolation network of conductive fillers (ferrite particles or carbon) within the polymer matrix can create effective pathways for this loss, making a significant contribution to total absorption, especially at higher frequencies [59]. This mechanism can be optimized by controlling the proportion of the conductive filler to avoid excessive reflection.

4.3. Impedance Matching

One of the most fundamental and critical challenges in the design of Radar Absorbing Materials (RAMs) is impedance matching. This phenomenon refers to the degree of compatibility between the intrinsic impedance of the absorbing material and the impedance of free space, which is approximately 377 ohms. When a significant impedance mismatch occurs, a substantial portion of the incident electromagnetic wave is reflected from the material's surface, leading to minimal energy absorption. This principle is analogous to a sound wave bouncing back from a rigid wall; the greater the difference in rigidity (impedance), the greater the reflection. Therefore, the key to ensuring effective microwave absorption is to design a material that "deceives" the incoming waves, making them feel as if they are entering the same medium as air, thereby minimizing reflection at the interface [46].

While ferrites like nickel ferrite possess excellent magnetic loss, they often have a low permittivity, which can result in a significant impedance mismatch with air. Conversely, pure dielectric materials have a high permittivity but low magnetic loss, making them equally suboptimal. This challenge often limits the performance of single-component microwave absorbing materials, which rarely achieve effective broadband absorption. To overcome this limitation, research has increasingly focused on composite materials that combine different material types, such as a blend of magnetic and dielectric components, to create a synergy that balances impedance.

This is where nickel ferrite-polymer nanocomposites play a crucial role. The dielectric polymer matrix functions to balance the overall impedance of the material. By incorporating nickel ferrite particles, which have high permeability, into the polymer matrix, the ratio of the composite's permittivity (εr) and permeability (μr) can be precisely tuned [20], [23]. The polymer helps to reduce the composite's total permittivity, bringing it closer to a value that is balanced with its permeability, allowing the material to meet the criteria for impedance matching. The synergy between the magnetic loss in the ferrite and the dielectric loss in the polymer enables the waves to be efficiently trapped and dissipated within the material, rather than being reflected back.

To achieve ideal impedance matching in practice, researchers employ various strategies. One is to optimize the mass ratio of the filler to the polymer matrix [60]. An excessive amount of nickel ferrite can increase permeability disproportionately, while too little can diminish magnetic loss. Another increasingly popular strategy is the design of multi-layered or core-shell architectures. These structures create a gradual impedance gradient, allowing microwaves to smoothly enter the material through an outer layer that is impedance-matched to air, and then pass into inner layers that are designed for high absorption loss [61].

This sophisticated approach is a highly effective way to achieve both broadband absorption and exceptional performance.

4.4. Reflection Loss (RL)

The primary quantitative parameter used to evaluate RAM performance is Reflection Loss (RL), typically expressed in decibels (dB). RL indicates how much of the incident electromagnetic wave is absorbed: (1) RL < −10 dB: More than 90% of the wave is absorbed, (2) RL < −20 dB: Absorption efficiency exceeds 99%, (3) RL < −40 dB: Considered exceptionally high and ideal for advanced applications such as stealth technology and high-intensity electromagnetic shielding.

Nickel ferrite–polymer nanocomposites, particularly those engineered with advanced nanostructures such as core–shell architectures or thin-film layers, have demonstrated RL values ranging from −10 dB to as low as −45 dB across the 2–18 GHz frequency range. These results confirm their excellent performance in diverse applications, including electromagnetic interference (EMI) shielding, military stealth systems, and high-frequency communication devices.

5. SYNTHESIS TECHNIQUE AND STRUCTURAL CONTROL

The performance of microwave absorbing materials is not solely determined by their chemical composition but is also highly dependent on structural parameters such as particle size, morphology, crystallinity, and phase distribution. Therefore, selecting the appropriate synthesis method is essential for tailoring the micro- and macrostructure of nickel ferrite-based materials to meet specific functional requirements in RAM applications. Several synthesis techniques have been employed to achieve precise structural control.

5.1. Coprecipitation

The coprecipitation method is widely used due to its simplicity, cost-effectiveness, and scalability [28]. This technique involves mixing metal precursor solutions (typically nickel and iron salts) and reacting them with a base to form a metal hydroxide precipitate. It allows good control over the stoichiometry and particle size of the resulting product. Post-synthesis thermal treatment (annealing) is usually required to enhance crystallinity and promote the formation of the spinel ferrite phase. A major advantage of this method is its ability to produce nanoparticles with narrow size distributions, making it suitable for large-scale production of nanostructured RAMs.

5.2. Sol-Gel

The sol-gel method is a chemical synthesis technique that relies on the formation of a colloidal suspension (sol) followed by its gelation into a continuous solid network (gel) [20]. This process typically involves the hydrolysis and condensation reactions of metal alkoxide or metal salt precursors in a liquid medium. Upon drying and subsequent calcination at high temperatures, the organic components are removed, and the gel transforms into a dense, amorphous or crystalline powder.

A key advantage of the sol-gel method is its ability to produce highly homogeneous materials at a molecular level, as the precursors are mixed in a liquid state. This molecular-scale mixing results in excellent compositional control and uniformity of the final product. Furthermore, this method is highly versatile and allows for the fabrication of various material forms, including thin films, fibers, and powders. However, a major drawback is the significant shrinkage and potential for cracking during the drying and calcination stages, which can affect the final morphology and introduce defects.

5.3. Hydrothermal

In contrast to the sol-gel method, the hydrothermal method operates under a fundamentally different principle. It is a "bottom-up" approach conducted in a sealed, high-pressure vessel (autoclave) using an aqueous medium [31]. The precursors are heated to temperatures well above water's normal boiling point (typically 100-300 °C), significantly increasing the solvent's reactivity and the solubility of the reactants. This creates a supercritical or subcritical fluid state that facilitates the direct crystallization of nanoparticles.

The primary strength of the hydrothermal method lies in its ability to directly synthesize highly crystalline, phase-pure materials at relatively low temperatures without the need for post-synthesis annealing. This is particularly advantageous for creating unique morphologies (e.g., nanorods, nanosheets, and hollow spheres) with a narrow size distribution, as the high pressure and controlled temperature allow for precise management of the crystal growth kinetics. The absence of high-temperature steps also helps in preventing particle agglomeration, leading to a more uniform and well-defined product.

5.4. Ball Milling and Solid-State Reaction

Although less commonly used for nanoscale RAMs, ball milling and solid-state reactions remain viable for bulk production [56]. These methods typically yield materials with broader particle size distributions and lower crystallinity. However, they are still useful for applications that do not require highly tailored nanostructures. Ball milling promotes homogeneous mixing of precursors, while solid-state reactions offer a solvent-free synthesis route, albeit at the cost of requiring high processing temperatures.

Ultimately, the choice of synthesis technique should align with the desired end-use—whether it be ultra-thin layered structures, flexible polymer-based absorbers, or large-volume structural electromagnetic shields. Hybrid synthesis approaches (e.g., hydrothermal-in-situ or sol-gel combined with polymerization) are also frequently employed to achieve optimal composite architectures for high-performance RAMs.

5.5. In-Situ Polymerization

This approach simultaneously synthesizes the conductive polymer (such as polyaniline or polypyrrole) and incorporates ferrite nanoparticles in a single step. In this method, ferrite particles are uniformly coated with a polymer layer, resulting in core–shell or layered composite structures [59], [62]. The strong interfacial interaction between the magnetic and dielectric components enhances microwave absorption by integrating magnetic and conductive loss mechanisms within a single composite matrix.

The choice of synthesis method greatly influences the structural, magnetic, and dielectric properties of nickel ferrite. **Table 4** summarizes the main advantages and disadvantages of the commonly employed synthesis techniques reported for $NiFe_2O_4$.

Table 4. Advantages and disadvantages of various synthesis methods for nickel ferrite

Method	Advantages	Disadvantages
Co-precipitation	• Simple, low-cost, and scalable process. • Good control over stoichiometry. • Produces nanoparticles with relatively uniform size.	• Often leads to particle agglomeration. • Requires post-synthesis calcination, which may increase particle size. • Sensitive to pH and reaction conditions.
Sol–gel	• Excellent compositional homogeneity. • Low processing temperature. • Allows fine control of microstructure and porosity.	• Relatively expensive precursors. • Long processing time due to gelation and drying steps. • Shrinkage and cracking may occur during drying.
Hydrothermal/ Solvothermal	• Produces highly crystalline nanoparticles without high-temperature calcination. • Enables control over particle morphology and size. • Suitable for producing well-dispersed nanoparticles.	• Requires high-pressure autoclaves (safety concern). • Limited scalability for mass production. • Relatively high synthesis time.
Microwave-assisted synthesis	• Rapid heating and shorter reaction time. • Energy-efficient and environmentally friendly. • Can yield nanoparticles with narrow size distribution.	• Requires specialized equipment. • Difficult to scale up. • Possible non-uniform heating at larger volumes.
Combustion synthesis	• Very fast reaction and high yield. • Produces fine particles with high surface area. • Low cost and simple setup.	• Poor control over particle size distribution. • May result in structural defects and impurities. • Often requires additional calcination for crystallinity.
Mechanical milling (High-energy ball milling)	• Simple and inexpensive technique. • Useful for large-scale production. • Can be used to modify particle size and induce defects beneficial for magnetic loss.	• Produces broad particle size distribution. • High possibility of contamination from milling media. • Requires long milling time and high energy consumption.
Spray pyrolysis	• Continuous and scalable production. • Can produce spherical, uniform particles. • Good compositional control.	• Requires specialized atomization equipment. • High processing temperature. • May produce hollow or porous particles that reduce density.

Table 5. Microwave absorption performance of $NiFe_2O_4$ and its composites prepared by different synthesis methods

Material	Synthesis Method	Size (nm)	RL (dB)	Frequency (GHz)	Thickness (mm)	Refs.
$NiFe_2O_4$	Sol-gel	66.1	-35.2	3.5	3.5	[30]
$NiFe_2O_4$	Coprecipitation	5.9	-24.0	9.5-12	3.5	[63]
$NiFe_2O_4$	Solid-state reaction	863	-	8-12	2.0	[64]
$Ni_xFe_{3-x}O_4$	Solid-state reaction	17	-28.0	10.98	2.0	[65]
$NiFe_2O_4$/PANI	Sol-gel	28	-59.1	10.7	2.1	[44]
Epoxy/Graphene/ $NiFe_2O_4$	Coprecipitation	75	-14.5	11.75	-	[45]
$NiFe_2O_4$/RGO	Coprecipitation	50	-60.0	0-20	0.13	[46]
$NiFe_2O_4$/MWCNTs	Hydrothermal	-	-19.0	11.3	1.5	[66]
$NiFe_2O_4$/Polystyrene	PAG	51	-13	11.5	2.9	[50]

Metal substitution in nickel ferrite ($NiFe_2O_4$) has been shown to significantly influence its microwave absorption performance, particularly the bandwidth of radar absorbing materials (RAMs). Substituting Ni^{2+} or Fe^{3+} ions with other transition or rare-earth metal ions can alter the balance between dielectric and magnetic losses, modify anisotropy, and improve impedance matching. These changes broaden the effective absorption bandwidth by enabling multiple resonance mechanisms across a wider frequency range. In general, suitable cation substitution enhances microwave attenuation and allows $NiFe_2O_4$-based composites to cover both X-band and other frequencies more effectively.

Table 5 presents the microwave absorption performance of $NiFe_2O_4$ and its composites prepared by various synthesis methods. The comparison includes particle size, minimum reflection loss (RL), effective frequency range, and sample thickness, highlighting the influence of synthesis approaches on absorber efficiency.

6. CHALLENGE AND FUTURE PERSPECTIVES

6.1. Challenges in Developing Nickel Ferrite-Based RAMs

Limited bandwidth. A major limitation is the narrow operational frequency range of many ferrite-based RAMs. Most are effective only in a specific frequency band, restricting their utility in modern radar systems that operate over multiple frequency bands [67].

Thermal Stability. Conductive polymers such as PPy and PANi, often used in composites, exhibit poor thermal stability. At elevated temperatures (>200 °C), these polymers may degrade, compromising the structural integrity and absorption performance of the material [68].

Mechanical Properties. There is often a trade-off between flexibility and mechanical strength. Polymer-based RAMs are generally flexible but may lack sufficient resistance to mechanical stress, deformation, or harsh environmental conditions, limiting their use in outdoor or structural applications [69].

Scalability dan Production Cost. Techniques like sol-gel [35], hydrothermal synthesis [70], and coprecipitation often require precise reaction conditions, extended processing times, and expensive reagents, making them challenging to scale up for industrial production. Efficient, low-cost synthesis methods are therefore needed.

6.2. Future Research Directions

To overcome the aforementioned challenges, several innovative strategies have been proposed to enhance the performance, stability, and practical applicability of nickel ferrite-based RAMs. One promising approach is the hybridization of ferrite–polymer composites with carbonaceous materials such as graphene, carbon nanotubes (CNTs), or carbon black [71] These hybrids not only improve electrical conductivity and broaden the absorption bandwidth, but also enhance thermal and mechanical stability by promoting interfacial polarization and facilitating better impedance matching. In parallel, recent advances in additive manufacturing have enabled the precise fabrication of RAM structures using ferrite–polymer composite inks, allowing the design of complex geometries specifically tailored for stealth and electromagnetic shielding applications. Another avenue of research involves the introduction of novel dopants, such as La^{3+}, Ce^{3+}, and V^{5+}, which can synergistically tune the dielectric and magnetic properties of nickel ferrite, thereby enabling multiband absorption essential for next-generation communication and radar technologies.

Furthermore, increasing attention has been directed toward the integration of ferrite–polymer composites into flexible and wearable electronic systems, where their lightweight nature, environmental stability, and mechanical robustness are critical for real-world deployment. With these advances in materials engineering and processing technologies, nickel ferrite-based RAMs are expected to transition from laboratory-scale developments to commercially viable solutions, addressing urgent demands across defense, telecommunications, and modern electronic industries.

7. CONCLUSION

Nickel ferrite-based nanopolymer composites represent a leading class of materials for the development of high-performance radar absorbing materials (RAMs) due to their tunable magnetic and dielectric properties. Structural engineering approaches, such as metal ion doping and the formation of conductive polymer composites, have demonstrated significant improvements in microwave absorption efficiency. These enhancements arise from better impedance matching, dual-loss mechanisms (magnetic and dielectric), and increased absorption across specific frequency ranges.

Nevertheless, technical challenges such as limited absorption bandwidth, thermal and mechanical instability of polymer components, and the complexity of industrial-scale synthesis remain to be addressed. Future research should focus on deeper understanding of structure–property relationships, the development of eco-friendly and scalable synthesis routes, and the incorporation of carbon-based hybrid structures to expand the application scope.

SUPPROTING INFORMATION

There is no supporting information in this paper. Data supporting the findings of this study are available upon request from the authors (YBA).

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CONFLICT OF INTEREST

There was no conflict of interest in this study. All authors have read and agreed to the published version of the manuscript.

AUTHOR CONTRIBUTIONS

TBP conceived the idea and wrote the original draft. AH & HR contributed to the data collection and review of the literature. RB and YBA supervised the project and provided critical revisions to the manuscript.

REFERENCES

[1] Houbi, A., Aldashevich, Z.A., Atassi, Y., Telmanovna, Z.B., Saule, M. and Kubanych, K. 2021. Microwave absorbing properties of ferrites and their composites: A review. *J. Magn. Magn. Mater.* 529. 167839. doi: https://doi.org/10.1016/j.jmmm.2021.167839

[2] Rybicki, T., Stempien, Z. and Karbownik, I. 2021. EMI Shielding and absorption of electroconductive textiles with PANI and PPy conductive polymers and numerical model approach. *Energies.* 14(22). 7746. https://doi.org/10.3390/en14227746

[3] Imran Din, M., Rafique, F., Hussain, M.S., Arslan Mehmood, H. and Waseem, S., 2019. Recent developments in the synthesis and stability of metal ferrite nanoparticles. *Sci. Prog.* 102(1). 61–72. https://doi.org/10.1177/0036850419826799

[4] Salih, S.J. and Mahmood, W.M. 2023. Review on magnetic spinel ferrite (MFe_2O_4) nanoparticles: from synthesis to application. *Heliyon.* 9(6). e16601. https://doi.org/10.1016/j.heliyon.2023.e16601

[5] Prekodravac Filipovic, J., Milenkovic, M., Kepic, D., Dorontic, S., Yasir, M., Nardin, B. and Jovanovic, S., 2025. Electromagnetic interference in the modern era: concerns, trends, and nanomaterial-based solutions. *Nanomaterials.* 15(20). 1558. https://doi.org/10.3390/nano15201558

[6] Abubakar, I., Din, J., Alhilali, M. and Lam, H.Y., 2017. Interference and electromagnetic compatibility challenges in 5G wireless network deployments. Indones. *J. Electr. Eng. Comput. Sci.* 5(3). 612-621. https://doi.org/10.11591/ijeecs.v5.i3.pp612-621

[7] Yustanti, E., Noviyanto, A., Chotimah, L.C., Saputra, M.A.R., Randa, M. and Manawan, M. 2022. Increased electromagnetic wave absorption through controlled sonication processing on $BaFe_{11.2}Mg_{0.4}Al_{0.4}O_{19}$ nanoparticles. *Coatings.* 12(9). 1367. https://doi.org/10.3390/coatings12091367

[8] Hwata, C., Rushingabigwi, G., Gatera, O., Mukalinyigira, D., Twizere, C., Thomas, B.N. and Peluffo-Ord'onez, D.H. 2025. Internet of things-based electromagnetic compatibility monitoring (IEMCM) architecture for biomedical devices. *Appl. Sci.* 15(22). 12337. https://doi.org/10.3390/app152212337

[9] Yucheng, L. and Yubin, L. 2010. Design strategy of anti-electromagnetic interference for microcomputer relay protection system. In *2010 International Forum on Information Technology and Applications.* 2. 180-183. https://doi.org/10.1109/IFITA.2010.78

[10] Barmore, W., Patel, H., Voong, C., Tarallo, C. and Calkins Jr, J.B. 2022. Effects of medically generated electromagnetic interference from medical devices on cardiac implantable electronic devices: A review. *World J. Cardiol.* 14(8). 446–453. https://doi.org/10.4330/wjc.v14.i8.446

[11] Perez, R. 2023. Analyzing fault propagation and designing fault containment for aerospace. In *2023 IEEE Aerospace Conference.* 1-8. https://doi.org/10.1109/AERO55745.2023.10115842

[12] Pavlík, M., Bereš, M. and Beňa, Ľ. 2024. The influence of various commonly used building materials on the shielding effectiveness, reflection and absorption of the electromagnetic wave. Appl. Sci. 14(6). 2521. https://doi.org/10.3390/app14062521

[13] Kumar, S., Kumar, B., Sehgal, R., Wani, M.F., Kumar, D., Sharma, M.D., Singh, V., Sehgal, R. and Kumar, V. 2023. Advantages and disadvantages of metal nanoparticles. In *Nanoparticles reinforced metal nanocomposites: mechanical performance and durability* (pp. 209-235). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-9729-7_7

[14] Cheng, J., Li, C., Xiong, Y., Zhang, H., Raza, H., Ullah, S., Wu, J., Zheng, G., Cao, Q., Zhang, D. and Zheng, Q. 2022. Recent advances in design strategies and multifunctionality of flexible electromagnetic interference shielding materials. *Nano-Micro Lett.* 14(1). 80. https://doi.org/10.1007/s40820-022-00823-7

[15] Sambhudevan, S., 2021. Ferrite-based polymer nanocomposites as shielding materials: a review. *Chem. Pap.* 75(8). 3697-3710. https://doi.org/10.1007/s11696-021-01664-1

[16] Gheisari, K., Javadpour, S., Shokrollahi, H. and Hashemi, B., 2008. Magnetic losses of the soft magnetic composites consisting of iron and Ni–Zn ferrite. *J. Magn. Magn. Mater.* 320(8). 1544-1548. https://doi.org/10.1016/j.jmmm.2008.01.005

[17] Al-Saleh, M.H., Saadeh, W.H. and Sundararaj, U., 2013. EMI shielding effectiveness of carbon based nanostructured polymeric materials: a comparative study. *Carbon.* 60. 146-156. https://doi.org/10.1016/j.carbon.2013.04.008

[18] Aritonang, S., Hijrianisa, A., Pratita, E., Ningrum, H.S. and Pangestu, B.B. 2024. Drone berbahan komposit serat rami dengan karbon aktif-barium m-heksaferit sebagai radar absorbing material. *Jurnal Rekayasa Material, Manufaktur dan Energi.* 7(1). 35-43. https://doi.org/10.30596/rmme.v7i1.17283

[19] Kim, S.H., Lee, S.Y., Zhang, Y., Park, S.J. and Gu, J. 2023. Carbon-based radar absorbing materials toward stealth technologies. *Adv. Sci.* 10(32). 2303104. https://doi.org/10.1002/advs.202303104

[20] Kostishin, V.G., Isaev, I.M. and Salogub, D.V. 2024. Radio-absorbing magnetic polymer composites based on spinel ferrites: a review. *Polymers.* 16(7). 1003. https://doi.org/10.3390/polym16071003

[21] Khedr, M.H., Omar, A.A. and Abdel-Moaty, S.A. 2006. Magnetic nanocomposites: preparation and characterization of Co-ferrite nanoparticles. *Colloids Surfaces A Physicochem. Eng. Asp.* 281(1–3). 8–14. https://doi.org/10.1016/j.colsurfa.2006.02.005

[22] Nha, T.T.N., Prakash, S.H., Roopan, S.M., Samuel, J.J., Toan, D.N., Khan, D.T., Bich, D.D., Thanh, T.D., Ngan, L.T.T., Manh, D.H. and Phong, P.T. 2025. Microwave-assisted co-precipitation synthesis of MFe_2O_4 nanoferrites (M= Co and Mn) using biogenic coir extract and their physical characterization. *RSC Adv.* 15(36). 29571-29592. https://doi.org/10.1039/D5RA04897D

[23] Malere, C.P., Donati, B., Eras, N., Silva, V.A. and Lona, L.F. 2022. Electromagnetic evaluation of radar absorbing materials based on conducting polypyrrole and organic–inorganic nanocomposite of polypyrrole/kaolinite. *J. Appl. Polym. Sci.* 139(17). 52023. https://doi.org/10.1002/app.52023

[24] Dubey, V. and Kain, V. 2018. Synthesis of magnetite by coprecipitation and sintering and its characterization. *Mater. Manuf. Process.* 33(8). 835-839. https://doi.org/10.1080/10426914.2017.1401720

[25] Dudhal, R.D., Patade, S., Andhare, D., Paralikar, R., Chilwar, R. and More, S.D. 2020. Influence of fuel to metal nitrate ratio on the structural properties of nickel ferrite. *J. Phys. Conf. Ser.* 1644(1). 012011. https://doi.org/10.1088/1742-6596/1644/1/012011

[26] Abd-Elkader, O.H., Deraz, N.M. and Aleya, L. 2023. Effects of zinc substitution on the microstructural and magnetic characteristics of cubic symmetry nickel ferrite system. *Symmetry*. 15(5). 975. https://doi.org/10.3390/sym15050975

[27] Li, J., Zhou, D., Wang, P.J., Du, C., Liu, W.F., Su, J.Z., Pang, L.X., Cao, M.S. and Kong, L.B. 2021. Recent progress in two-dimensional materials for microwave absorption applications. *Chem. Eng. J.* 425. 131558. https://doi.org/10.1016/j.cej.2021.131558

[28] Kavitha, S. and Kurian, M. 2019. Effect of zirconium doping in the microstructure, magnetic and dielectric properties of cobalt ferrite nanoparticles. *J. Alloys Compd.* 799. 147-159. https://doi.org/10.1016/j.jallcom.2019.05.183

[29] Habibi, M.H. and Fakhri, F. 2017. Low temperature preparation, characterization, magnetic measurements, thermal, optical, morphological and photo-catalytic properties of nano-size single phase nickel ferrite $NiFe_2O_4$. *J. Mater. Sci. Mater. Electron.* 28(18). 13455-13463. https://doi.org/10.1007/s10854-017-7184-z

[30] Aggarwal, N. and Narang, S.B. 2020. X-band microwave

analysis and characterization of zinc substituted nickel ferrites prepared by sol–gel citrate route. *J. Electron. Mater.* 49(1). 668-680. https://doi.org/10.1007/s11664-019-07694-6

[31] Narang, S.B. and Pubby, K. 2021. Nickel spinel ferrites: a review. *J. Magn. Magn. Mater.* 519. 167163. https://doi.org/10.1016/j.jmmm.2020.167163

[32] Isasi, J., Arévalo, P., Martin, E. and Martín-Hernández, F. 2019. Preparation and study of silica and APTES–silica-modified $NiFe_2O_4$ nanocomposites for removal of Cu^{2+} and Zn^{2+} ions from aqueous solutions. *J. Sol-Gel Sci. Technol.* 91(3). 596-610. https://doi.org/10.1007/s10971-019-05067-3

[33] Sagadevan, S., Chowdhury, Z.Z. and Rafique, R.F. 2018. Preparation and characterization of nickel ferrite nanoparticles via co-precipitation method. *Mater. Res.* 21(2). e20160533. https://doi.org/10.1590/1980-5373-mr-2016-0533

[34] Ismail, I. and Azis, R.A.S. 2024. A review of magnetic nanocomposites for EMI shielding: synthesis, properties, and mechanisms. *J. Mater. Sci.* 59(13). 5293-5329. https://doi.org/10.1007/s10853-024-09527-2

[35] Bokov, D., Turki Jalil, A., Chupradit, S., Suksatan, W., Javed Ansari, M., Shewael, I.H., Valiev, G.H. and Kianfar, E. 2021. Nanomaterial by sol-gel method: synthesis and application. *Adv. Mater. Sci. Eng.* 2021(1). 5102014. https://doi.org/10.1155/2021/5102014

[36] Yue, X., Fan, J. and Xiang, Q. 2022. Internal electric field on steering charge migration: modulations, determinations and energy-related applications. *Adv. Funct. Mater.* 32(12). 2110258. https://doi.org/10.1002/adfm.202110258

[37] Samet, M., Kallel, A. and Serghei, A. 2022. Maxwell-Wagner-Sillars interfacial polarization in dielectric spectra of composite materials: Scaling laws and applications. *J. Compos. Mater.* 56(20). 3197-3217. https://doi.org/10.1177/00219983221090629

[38] Khoreem, S.H. and Al-Hammadi, A.H. 2025. Tailoring the functional properties of $BaNi_{2-x}Zn_xFe_{16}O_{27}$ ferrites via ceramic route for advanced electronic and energy applications. *Discov. Mater.* 5(1). 173. https://doi.org/10.1007/s43939-025-00374-9

[39] Gómez, C.A.P., McCoy, J.J., Weber, M.H. and Lynn, K.G. 2019. Effect of Zn for Ni substitution on the properties of Nickel-Zinc ferrites as studied by low-energy implanted positrons. *J. Magn. Magn. Mater.* 481. 93-99. https://doi.org/10.1016/j.jmmm.2019.03.002

[40] Borge-Duran, I., Paul, A. and Grinberg, I. 2023. From Non-Magnetic to Magnetic: A First-Principles Study of the Emergence of Magnetism in 2D $(Nb_{1-x}Ti_x)$ 4C3 MXenes. *Chem. Mater.* 35(18). 7442-7449. https://doi.org/10.1021/acs.chemmater.3c00367

[41] Zhou, W., Cao, G., Yuan, M., Zhong, S., Wang, Y., Liu, X., Cao, D., Peng, W., Liu, J., Wang, G. and Dang, Z.M. 2023. Core–shell engineering of conductive fillers toward enhanced dielectric properties: a universal polarization mechanism in polymer conductor composites. *Adv. Mater.* 35(2). 2207829. https://doi.org/10.1002/adma.202207829

[42] Moučka, R., Sedlačík, M., Prokeš, J., Kasparyan, H., Valtera, S. and Kopecký, D. 2020. Electromagnetic interference shielding of polypyrrole nanostructures. *Synth. Met.* 269. 116573. https://doi.org/10.1016/j.synthmet.2020.116573

[43] Aytaç, A., İpek, H., Aztekin, K., Aytav, E. and Çanakçı, B. 2020. A review of the radar absorber material and structures. *Sci. J. Mil. Univ. L. Forces.* 198(4). 931–946. https://doi.org/10.5604/01.3001.0014.6064

[44] Sulaiman, J.M. and Calinescu, I. 2022. Electromagnetic interference (EMI) shielding and microwave absorption properties of nickel ferrite $NiFe_2O_4$/PANI-PTSA nanocomposite. *Adv. Mater. Process. Technol.* 8(2). 1312-1323. https://doi.org/10.1080/2374068X.2020.1856635

[45] Manobalan, S., Mahender, C., Rajan Babu, D., Rahaman, A., Sreekanth, M.S., Sharma, D., Bose, S. and Sumangala, T.P. 2022. The mechanical, dielectric, and EMI shielding properties of nickel ferrite (NiF)/graphene (Gr)-doped epoxy composites. *J. Inorg. Organomet. Polym. Mater.* 32(10). 4077-4091. https://doi.org/10.1007/s10904-022-02419-5

[46] Mansha, A., Zubair, K., Rehan, Z.A., Shakir, H.F., Javed, T., Shabbir, R., Mustafa, S.K., Mora-Poblete, F., Zhou, J.R., Kumar, U. and Al-Harbi, M.S. 2021. Synthesis of nickel spinel ferrites nanoparticles coated with thermally reduced graphene oxide for EMI shielding in the microwave, UV, and NIR regions. *Polymers.* 13(19). 3316. https://doi.org/10.3390/polym13193316

[47] Meaz, T.M., Saafan, S.A., El-Ghazzawy, E.H., Ayad, M.M. and El Nimr, M.K. 2012. Comparative study of dielectric properties of (Ni Zn ferrite nanoparticles/polypyrrole) composites with different PPy percentages. *J. Am. Sci.* 8(8). 1035-1041.

[48] Saini, M., Shukla, R. and Kumar, A. 2019. Cd^{2+} substituted nickel ferrite doped polyaniline nanocomposites as effective shield against electromagnetic radiation in X-band frequency. *J. Magn. Magn. Mater.* 491. 165549. https://doi.org/10.1016/j.jmmm.2019.165549

[49] Kostishyn, V.G., Isaev, I.M., Shakirzyanov, R.I., Salogub, D.V., Kayumova, A.R. and Olitsky, V.K. 2023. Radar absorbing properties of polyvinyl alcohol/Ni–Zn ferrite-spinel composite. *Tech. Phys.* 68(2). S178-S184. https://doi.org/10.21883/tp.2022.01.52540.217-21

[50] Zhao, H., Sun, X., Mao, C. and Du, J. 2009. Preparation and microwave–absorbing properties of $NiFe_2O_4$-polystyrene composites. *Phys. B Condens. Matter.* 404(1). 69-72., https://doi.org/10.1016/j.physb.2008.10.006

[51] Sulistiyo, H., Farhan, M.F., Soraya, N.A. and Gunadi, G.I. 2022. Material lapisan anti-radar untuk menyamarkan kawasan strategis dan sarana pendukung militer (markas TNI, hanggar pesawat tempur, hanggar tank dan gudang amunisi). *J. Kewarganegaraan.* 6(4). 6642-6649. https://doi.org/10.31316/jk.v6i4.4223

[52] Thomas, P., Abdulhakim, L.V., Pushkaran, N.K. and Karuvandi, A.C. 2020. Wideband radar absorbing structure using polyaniline-graphene nanocomposite. C. 6(4). 72. https://doi.org/10.3390/c6040072

[53] Zong, M., Huang, Y., Ding, X., Zhang, N., Qu, C. and Wang, Y. 2014. One-step hydrothermal synthesis and microwave electromagnetic properties of RGO/$NiFe_2O_4$ composite. *Ceram. Int.* 40(5). 6821-6828. https://doi.org/10.1016/j.ceramint.2013.11.145

[54] Iranmanesh, P., Yazdi, S.T., Mehran, M. and Saeednia, S. 2018. Superior magnetic properties of Ni ferrite nanoparticles synthesized by capping agent-free one-step coprecipitation route at different pH values. *J. Magn. Magn. Mater.* 449. 172-179. https://doi.org/10.1016/j.jmmm.2017.10.040

[55] Jahanbin, T., Hashim, M. and Mantori, K.A. 2010. Comparative studies on the structure and electromagnetic properties of Ni–Zn ferrites prepared via co-precipitation and conventional ceramic processing routes. *J. Magn. Magn. Mater.* 322(18). 2684-2689. https://doi.org/10.1016/j.jmmm.2010.04.008

[56] Chan, Y.L., You, K.Y., Mayzan, M.Z.H., Jusoh, M.A., Abbas, Z. and Esa, F. 2020. Investigation into return loss characteristic of graphene oxide/zinc ferrite/epoxy composite at X-band frequency. *J. Appl. Sci. Eng.* 23(4). 593-602. https://doi.org/10.6180/jase.202012_23(4).0003

[57] Hou, T., Jia, Z., Wang, B., Li, H., Liu, X., Bi, L. and Wu, G. 2021. MXene-based accordion 2D hybrid structure with $Co_9S_8/C/Ti_3C_2T_x$ as efficient electromagnetic wave absorber. *Chem. Eng. J.* 414. 128875. https://doi.org/10.1016/j.cej.2021.128875

[58] Li, J., Zhou, D., Wang, P.J., Du, C., Liu, W.F., Su, J.Z., Pang, L.X., Cao, M.S. and Kong, L.B. 2021. Recent progress in two-dimensional materials for microwave absorption applications. *Chem. Eng. J.* 425. 131558. https://doi.org/10.1016/j.cej.2021.131558

[59] Gu, Q., Jafarian, M., Afghahi, S.S.S., Atassi, Y. and Al-Qassar, R. 2020. Tuning the impedance matching characteristics of microwave absorbing paint in X-band using copper particles and polypyrrole coating. *Mater. Res. Bull.* 125. https://doi.org/110780.10.1016/j.materresbull.2020.110780

[60] Planes, E., Gloaguen, F. and Flandin, L. 2015. Optimizing formulations of polymer composite with high filler content: Application to bipolar plate. *Compos. Sci. Technol.* 110. 17-25. https://doi.org/10.1016/j.compscitech.2015.01.009

[61] Xu, Z., Li, J., Li, J., Du, J., Li, T., Zeng, W., Qiu, J. and Meng, F. 2023. Bionic structures for optimizing the design of stealth materials. *Phys. Chem. Chem. Phys.* 25(8). 5913-5925. https://doi.org/10.1039/D2CP06086H

[62] Gill, N., Sharma, A.L., Gupta, V., Tomar, M., Pandey, O.P. and Singh, D.P. 2019. Enhanced microwave absorption and suppressed reflection of polypyrrole-cobalt ferrite-graphene nanocomposite in X-band. *J. Alloys Compd.* 797. 1190-1197.

https://doi.org/10.1016/j.jallcom.2019.05.176

[63] Zhu, W., Wang, L., Zhao, R., Ren, J., Lu, G. and Wang, Y. 2011. Electromagnetic and microwave-absorbing properties of magnetic nickel ferrite nanocrystals. *Nanoscale*. 3(7). 2862-2864. https://doi.org/10.1039/c1nr10274e

[64] Kartika, D.M., Rusmana, A. and Sumpena, P. 2021. Structural, magnetic, and X-band microwave absorbing properties of Ni-ferrites prepared using oxidized mill scales. *J. Elektron. Telekomun.* 21(1). 27-34. https://doi.org/10.14203/jet.v21.27-34

[65] Yunas, Y., Adi, W.A., Mashadi, M. and Rahmy, P.A. 2017. Magnetic and microwave absorption properties of nickel ferrite ($Ni_xFe_{3-x}O_4$) by HEM technique. *Malaysian J. Fundam. Appl. Sci.* 13(3). 203–206. https://doi.org/10.11113/mjfas.v13n3.553

[66] Guo, L., He, Y., Chen, D., Du, B., Cao, W., Lv, Y. and Ding, Z., 2021. Hydrothermal synthesis and microwave absorption properties of nickel ferrite/multiwalled carbon nanotubes composites. *Coatings*. 11(5). 534. https://doi.org/10.3390/coatings11050534

[67] Harris, V.G. 2011. Modern microwave ferrites. *IEEE Trans. Magn.* 48(3). 1075-1104. https://doi.org/10.1109/TMAG.2011.2180732

[68] Somboonsub, B., Srisuwan, S., Invernale, M.A., Thongyai, S., Praserthdam, P., Scola, D.A. and Sotzing, G.A., 2010. Comparison of the thermally stable conducting polymers PEDOT, PANi, and PPy using sulfonated poly (imide) templates. Polymer. 51(20). 4472-4476. https://doi.org/10.1016/j.polymer.2010.08.008

[69] Subudhi, P. and Punetha, D., 2023. Progress, challenges, and perspectives on polymer substrates for emerging flexible solar cells: A holistic panoramic review. *Prog. Photovoltaics Res. Appl.* 31(8). 753-789. https://doi.org/10.1002/pip.3703

[70] Darr, J.A., Zhang, J., Makwana, N.M. and Weng, X., 2017. Continuous hydrothermal synthesis of inorganic nanoparticles: applications and future directions. *Chem. Rev.* 117(17). 11125-11238. https://doi.org/10.1021/acs.chemrev.6b00417

[71] Koul, S.K., Praveen, M. and Karthikeya, G.S. 2025. *Microwave absorbers: materials engineering.* Springer. https://doi.org/10.1007/978-981-96-9596-6_6.