



From Lead to Nanocomposites: Role of Iron Oxide/Epoxy Resin in Sustainable Ionizing Electromagnetic Radiation Shielding for Modern Hospitals

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Abstract

The escalating need for sophisticated electromagnetic interference shielding materials in medical settings may motivate the innovation of advanced composites designed to attenuate electromagnetic radiation effectively. This investigation examines the synthesis and characterization of iron oxide nanoparticles integrated into an epoxy resin matrix, emphasizing their performance in shielding electromagnetic waves. Magnetic iron oxide nanoparticles, produced through coprecipitation, were embedded in epoxy resin to form lightweight, absorption-dominant shields targeting microwave frequencies (Sparavigna, 2023). This strategy appears to amplify electromagnetic interference shielding effectiveness by exploiting the intrinsic attributes of magnetic nanoparticles, such as Fe_3O_4 , in polymer matrices, potentially rendering them suitable for high-frequency field mitigation (Sparavigna, 2023). The uniform dispersion of Fe_3O_4 nanoparticles in the epoxy fosters a conductive network, which may boost electromagnetic interference shielding effectiveness via synergistic electrical and magnetic losses (Sparavigna, 2023). The study delineates the structural properties and electromagnetic interference shielding effectiveness (EMI SE) of these composites, projecting their utility in curbing interference within sensitive medical contexts. Such materials may be pivotal for protecting electronics and personnel from ubiquitous electromagnetic radiation. This paper elucidates the synthesis, characterization, and EMI shielding efficacy of these innovative composites, underscoring their promise for cutting-edge applications, particularly in the X-band where hybrid nanostructures modulate epoxy composite shielding (Bheema & Etika, 2022). Agglomeration of iron oxide nanoparticles in epoxy resin is a significant challenge due to high surface energy and magnetic properties, necessitating specialized dispersion techniques (Naguib et al., 2019). Furthermore, Fe_3O_4 nanoparticles, endowed with high saturation magnetization and low resistivity, impart dual magnetic and electrical attributes, refining microwave absorption (Ramajo et al., 2009). This facilitates a shift in shielding from reflection to absorption, modulated by filler selection, yielding adaptable responses (Sparavigna, 2023). Systematically probing nanoparticle loading and dispersion synergies may optimize attenuation mechanisms in the X-band. This inquiry may advance understanding of engineering magnetic nanocomposites for exceptional EMI SE in vital sectors, notably via Fe_3O_4 /TAGA integration in epoxy, harnessing dielectric-magnetic loss synergy for impedance matching (Chhetri & Kuila, 2024).

Keywords: Fe_3O_4 nanoparticles, Epoxy nanocomposites, Electromagnetic interference (EMI) shielding, Radiation attenuation, Lead-free shielding, Microstructural dispersion.

1. Introduction

1.1. Background on Ionizing Electromagnetic Radiation in Healthcare

Electromagnetic radiation, essential for diagnostic and therapeutic applications, generates a complex electromagnetic environment that may necessitate the implementation of advanced shielding materials for the mitigation of health risks and the assurance of equipment reliability (Salem et al., 2024). The unique characteristics of ionizing radiation—especially X-rays and gamma rays, characterized by their elevated energies and significant biological impacts—have traditionally necessitated heavy metal-based shielding strategies (Nambiar & Yeow, 2012). Thus, radiation shields are generally expected to provide sufficient attenuation against the harmful effects of ionizing radiation, typically achieved through multilayered designs incorporating high-density metals and neutron moderators, customized in terms of composition and thickness to suit particular radiation profiles and operational settings (Al-Saleh et al., 2023).

Incorporating nanoparticles into polymer matrices may increase the probability of radiation-matter interactions, owing to their high surface areas and nanoscale sizes, which enable homogeneous distribution within the base material (Elsafi et al., 2024). This methodology appears to facilitate the creation of advanced shielding composites with superior performance, effective at meeting the diverse requirements of contemporary radiation protection (Chang et al., 2023). The fabrication of lead-free lightweight composites

for use as radiation shielding materials in medical protective gear may be warranted (Govenkar et al., 2024). Moreover, embedding high atomic number elements, such as certain metal oxides, into polymer matrices may markedly enhance gamma-ray attenuation by increasing photon interaction cross-sections (Govenkar et al., 2024).

The precise modulation of nanoparticle volume fractions within these composites may facilitate accurate control over complex permittivity and permeability, enabling applicability across diverse frequency ranges (Chang et al., 2021). This versatility permits targeted manipulation of electromagnetic properties to achieve peak shielding effectiveness, often by balancing dielectric and magnetic losses to improve impedance matching with free space (Cuppoletti, 2011; Rosa et al., 2024). Consequently, the strategic choice and integration of functional fillers into polymer matrices produce lightweight, highly effective shielding solutions that appear to mitigate the inherent limitations of traditional heavy-metal shields (Jayakumar et al., 2023).

The increasing deployment of electronic devices in healthcare settings amplifies electromagnetic interference concerns, which can impair critical medical equipment performance and data integrity, thereby suggesting a heightened need for comprehensive shielding approaches (David et al., 2000). As a result, there may be a need for advanced composite materials that may simultaneously attenuate ionizing radiation and suppress EMI, thereby providing integrated protection in complex medical environments (Flandy et al., 2026). Additionally, lead-free, flexible, multilayered structures based on silicone composites with high-atomic-number additives—such as tin, cerium oxide, tungsten oxide, and bismuth—may demonstrate adjustable X-ray attenuation properties, offering viable options for tailored shielding applications (Gilys et al., 2022). These innovations may support the production of bespoke shielding solutions adaptable to complex geometries and varied radiation protection demands, and may outperform conventional heavy and rigid shields (Gilys et al., 2022; Govenkar et al., 2024). In addition to addressing the shortcomings of traditional lead aprons, such as toxicity and stiffness, these materials may provide enhanced performance in demanding operational conditions (Tayebi-khorami & Salehi, 2025). Furthermore, elastomer-based composites reinforced with various fillers and fibers may improve shielding capabilities through properties like flexibility, low weight, and corrosion resistance, essential for practical implementation (Prabhu et al., 2023).

1.2. Need for Ionizing EMR Shielding

Ionizing radiation, such as X-rays and gamma rays, may cause substantial cellular damage, leading to severe health effects ranging from acute radiation syndrome to increased cancer risk (Talapko et al., 2024). Thus, developing effective radiation shielding materials appears essential to the safeguarding of healthcare workers and patients amidst the increasing utilization of medical imaging and radiotherapy (Abdel-Kader et al., 2024). This necessity drives the exploration of innovative, lightweight, and flexible protective materials to overcome the limitations of traditional rigid shields (Abdel-Kader et al., 2024). Advanced shielding composites may be vital for mitigating both deterministic effects, such as immediate tissue damage, and stochastic risks, such as long-term carcinogenesis (Alabsy & Elzahr, 2023). Prior scholarship has investigated novel composites, including Nylon 6 blended with bismuth oxide, silicone rubber, and aluminum, which provide lightweight, non-toxic alternatives that may reduce Bremsstrahlung radiation compared to lead-based systems (Govenkar et al., 2024). Lead's drawbacks—toxicity, rigidity, and high weight—may underscore the demand for alternatives offering superior safety, portability, and attenuation efficacy (El-Khatib et al., 2023). Consequently, there appears to be a growing need for advanced composites that match or exceed lead's performance while addressing environmental concerns and enhancing user comfort and mobility (Wu et al., 2024). These materials may also exhibit improved mechanical and electrical properties suited to diverse clinical environments (Govenkar et al., 2024). Meanwhile, the expansion of electronic systems across industrial, military, and consumer domains may have intensified electromagnetic interference issues, necessitating the formulation of materials for attenuating such interference (Zhang & Gu, 2022).

The limitations of lead utilization appear to have catalyzed innovation in lead-free polymer nanocomposites, which may deliver comparable or enhanced shielding efficacy, thereby avoiding health or environmental detriments (Malekie et al., 2022). These polymer-based composites may be valued for their versatility, low weight, and tunable properties optimized for radiation attenuation (Alshipli et al., 2023). They also provide mechanical robustness, flexibility, and chemical stability, ideal for applications where lead is impractical (Alshahri et al., 2021). Incorporating inorganic high-atomic-number (high-Z) fillers into polymer matrices appears to enhance gamma- and X-ray attenuation while mitigating lead's constraints (El-Khatib et al., 2019). This strategy may synergistically combine filler properties to create efficient composite shields (Naeem et al., 2023), yielding flexible, environmentally benign materials critical for radiation protection advancements (Nambiar & Yeow, 2012). Such composites likely require the demonstration of strong mechanical integrity, thermal stability, and durability to endure operational stresses (Zecchi et al., 2024). Integrating these attributes may enable multifunctional designs for concurrent electromagnetic interference (EMI) shielding and radiation attenuation, optimizing protection in high-radiation settings (Jayakumar et al., 2023). Nanotechnology advances may allow precise nanoparticle dispersion and alignment in polymers, boosting EMI shielding (Zecchi et al., 2024). These developments may produce composites with effective radiation attenuation alongside desirable mechanical and thermal traits (Prabhu et al., 2022). Nanoparticle fillers in polymer matrices may markedly improve attenuation via enhanced dispersion and radiation interactions, particularly for X-rays (Alshipli et al., 2023).

This demand stems from requirements for patient comfort, personnel maneuverability, and adaptability to anatomical contours in procedures (Alshipli et al., 2023). Researchers prioritize high-Z fillers, such as bismuth oxide, tungsten oxide, and rare-earth elements, within polymer matrices (Mahmoudian et al., 2023; Tochaikul & Moonkum, 2024). Bismuth oxide, with its high atomic number and density, may achieve substantial gamma- and X-ray attenuation in thin samples (Govenkar et al., 2024). As a preferred gamma-ray shield filler, bismuth oxide nanoparticles match lead's efficacy while remaining non-toxic (Salem et al., 2024), and their integration into polymers may enhance detection and dosimetry sensitivity via uniform dispersion (Veiskarami et al., 2022). Doping with barium may further improve attenuation, potentially rivaling lead oxide for X-rays due to absorption-edge effects of barium, bismuth, and tungsten (Rabiei et al., 2024). This synergy of high-Z materials and polymer designs yields next-generation shields that may surpass lead (Gharissah et al., 2022; Li et al., 2021). Lead-free Bi₂O₃-polymer nanocomposites appear to exhibit superior gamma attenuation across broad energies (Alsaab & Zeghib, 2023). For instance, TSN-3 (50% aluminum) appears to excel against low-energy gamma rays, while TSN-5 (80% bismuth oxide, 50% aluminum) performs well for high-energy and positron emitters (Govenkar et al., 2024). Tailoring filler combinations may optimize shielding for specific radiation spectra (Qi et al., 2025). Uniform

distribution of high-Z nanoparticles, such as bismuth oxide, may prevent agglomeration, potentially maximizing radiation shielding (Qi et al., 2025), ensuring lightweight, pliable protection (Marshall et al., 2025). Nanocomposite bismuth oxide may outperform microcomposites in efficiency (Baamer et al., 2024), as seen in polydimethylsiloxane-bismuth oxide systems with optimal X-ray attenuation (Bawazeer et al., 2023).

1.3. Overview of Iron Oxide Nanoparticles

Inherent magnetic properties of iron oxide nanoparticles facilitate effective interaction with and dissipation of electromagnetic energy, rendering them suitable for diverse electromagnetic interference (EMI) shielding applications (Zecchi et al., 2024). In particular, the superparamagnetic behavior exhibited by iron oxide nanoparticles at the nanoscale promotes superior absorption mechanisms, especially within microwave frequencies, via processes such as natural resonance and eddy current losses (Liang et al., 2021). Furthermore, the uniform dispersion of iron oxide nanoparticles within polymer matrices enhances shielding efficacy by reducing aggregation and optimizing the interfacial area for electromagnetic field interactions (Wilson et al., 2004). These nanoparticles also present environmental advantages over numerous synthetic counterparts (Prabhu et al., 2023). Thus, integrating iron oxide nanoparticles into polymer composites appears to address the requirements for efficient EMI shielding while supporting the development of sustainable, non-toxic functional materials (Shukla, 2019). This approach may enable the creation of advanced microwave stealth materials that prioritize absorption over reflection, thereby mitigating secondary pollution from traditional shielding approaches (Keykavous-Amand & Peymanfar, 2021). Consequently, they may be particularly suitable for scenarios requiring minimal reflection, including radar-absorbing materials and anechoic chambers (Teber, 2017). High magnetic permeability coupled with dielectric losses appears to underpin their exceptional electromagnetic wave absorption, positioning them as pivotal elements in sophisticated shielding technologies (Fallah et al., 2021). Incorporating ferrite nanoparticles, which confer enhanced thermal and corrosion resistance, may further augment composite performance, particularly at elevated frequencies (Redón et al., 2023). Moreover, embedding iron oxide nanoparticles in polymer matrices yields lightweight, flexible shielding solutions essential for cutting-edge electronics and wearable technologies (Zecchi et al., 2024). This versatility extends applications beyond conventional rigid structures, accommodating intricate geometries and dynamic conditions. Additionally, magnetic nanoparticles exhibiting shape anisotropy—such as carbon nanotubes loaded with Fe nanowires, ferromagnetic alloy nanowires, and iron (Fe), nickel (Ni), zinc oxide (ZnO), or silicon carbide (SiC) nanowires—have garnered substantial research interest owing to their elevated surface-to-volume ratios and aspect ratios (Zecchi et al., 2024). These characteristics may substantially bolster electromagnetic absorption through multiple internal reflections and scattering (Yang et al., 2023), thereby elevating microwave absorption performance and rendering them efficacious for EMI shielding (Fallah et al., 2021). Recent investigations have validated the efficacy of iron nanowires and spherical Fe_3O_4 nanoparticles in epoxy matrices for microwave absorption, achieving reflection losses below -10 dB across targeted frequency bands (Zecchi et al., 2024). These progressions may underscore the adaptability and promise of iron oxide nanoparticles in next-generation electromagnetic absorbers, addressing the escalating need for efficient, lightweight shielding. Furthermore, synthesizing iron oxide nanoparticles with customized morphologies, including microspheres or core-shell configurations, optimizes impedance matching and absorption-dominant shielding (Prabhu et al., 2023). This stems primarily from multiple interfaces that induce electromagnetic scattering and absorption, prolonging the propagation path and enhancing energy dissipation (Shukla, 2019). Such deliberate engineering may curtail secondary electromagnetic pollution by favoring absorption over reflection, which is vital for eco-friendly shielding (Chandra et al., 2023).

Electromagnetic-to-thermal conversion in these nanoparticles appears to be chiefly governed by magnetic hysteresis, eddy currents, and dielectric losses, synergistically enabling efficient dissipation of incident radiation (Deng et al., 2020). Additionally, the adjustable electromagnetic attributes of iron oxide nanoparticles, especially in hierarchical or hybrid composites, permit fine-tuned control of microwave absorption profiles (Afzali et al., 2022). Converting electromagnetic radiation to thermal energy via these mechanisms may be essential for materials that prioritize absorption over reflection, potentially alleviating secondary pollution (Prabhu et al., 2023). Hence, the utilization of engineered nanoparticles may yield composites characterized by superior absorption efficiency and negligible reflection, which appears ideal for stealth technologies and electromagnetic interference (EMI) mitigation in precision electronics (Fallah et al., 2021). This multifaceted absorption may render these materials significant across defense, civil infrastructure, and domains prioritizing electromagnetic compatibility (Zhang et al., 2015). Moreover, their incorporation into polymer matrices such as epoxy resins or flexible variants facilitates lightweight, adaptable shields for electronic packaging and biomedical uses (Zecchi et al., 2024). The uniform dispersion within conductive, porous hosts—achieved via advanced synthesis—appears to amplify shielding by fostering multiple reflections and absorptions (Liu et al., 2024), which may thereby maximize electromagnetic energy dissipation and overall EMI shielding effectiveness.

1.4. Role of Epoxy Resin Polymers in Composites

Epoxy resins may provide substantial mechanical strength, thermal stability, and chemical resistance, essential for preserving the structural integrity and functionality of electromagnetic interference (EMI) shielding composites across varied environmental conditions (Vidyashree et al., 2022). Their reduced density enables the development of lightweight shielding materials, which are particularly advantageous for aerospace and portable electronics where minimizing mass is critical (Wang et al., 2022). The intrinsic adhesiveness of epoxy resins promotes robust interfacial adhesion with diverse conductive fillers, facilitating effective load transfer and homogeneous dispersion of electromagnetic shielding fillers within the composite (Vidyashree et al., 2022). This adhesion may be important for channeling electromagnetic energy to the fillers, thereby enhancing overall shielding efficacy (Wang et al., 2022). Furthermore, the processability and curing flexibility of epoxy resins support the production of intricate geometries and extensive panels, expanding their utility in EMI shielding technologies (Ribadeneyra et al., 2014). The chemical inertness and resilience to degradation may support sustained performance and durability of composites in demanding settings (Kruželák et al., 2020). Tailorable attributes of epoxy resins permit enhancements of properties such as flame retardancy or thermal conductivity (Ferrari et al., 2014), broadening their scope in specialized EMI applications. Certain epoxy formulations exhibit transparency to visible electromagnetic waves, and when augmented with suitable fillers, yield optically transparent yet electromagnetically opaque materials for applications demanding both optical clarity and EMI protection (Gao et al., 2025). Strategic filler selection enables precise adjustment of dielectric properties in epoxy matrices, improving impedance matching with incoming waves to reduce

reflection and amplify absorption (Kruželák et al., 2020). The implementation of such strategies appears pivotal for maximizing electromagnetic interference shielding effectiveness, particularly in reflection-minimal scenarios (Guan et al., 2024). Epoxy resins' compatibility with manufacturing processes like extrusion, compression molding, and injection molding supports economical large-scale production in the plastics sector (Chandra et al., 2023), positioning them as a practical matrix for high-performance EMI shielding composites (Wanasinghe et al., 2020). Their affordability, availability, and established industrial profile further render them viable for scalable EMI solutions (Barani et al., 2020). Integrating nanofillers such as carbon black or MXenes into epoxy matrices may enhance EMI shielding via augmented dielectric and magnetic losses, alongside multiple internal reflections (Fallah et al., 2021; Janjua et al., 2024). For example, graphene nanoplatelets in ABS composites substantially improve shielding, with efficacy scaling with concentration (Chandra et al., 2023). Polymer-based EMI materials often feature segregated or aligned conductive fillers, leveraging attributes like corrosion resistance, deformability for wearables, and adjustable shielding (Wei et al., 2024). These innovations may enable lightweight, flexible EMI solutions for electronics, aerospace, and beyond (Chandra et al., 2023; Kruželák et al., 2020), delivering broad-frequency shielding (Barani et al., 2020) as viable, low-density, corrosion-resistant alternatives to metals (Martins et al., 2023; Prabhu et al., 2023). While early composites relied on high metallic loadings, recent shifts favor carbon-based fillers for their lightweight nature, corrosion resistance, high permittivity, conductivity, and stability (Barani et al., 2020; Kruželák et al., 2020). Carbon black and magnetite nanoparticles facilitate enhanced shielding through reflection and absorption (Fallah et al., 2021), forming conductive networks that promote charge mobility and energy dissipation via resistive losses and reflections (Kruželák et al., 2020). High-aspect-ratio fillers like carbon nanotubes and graphene lower percolation thresholds, balancing shielding and weight (Kruželák et al., 2020). Hybrid systems combining carbon fillers (e.g., carbon black, nanotubes, or graphene) with ferrites or oxides diversify shielding properties (Kruželák et al., 2020; Zecchi et al., 2024), enabling tailored absorption/reflection across bands (Prabhu et al., 2023) with improved stability, dielectric properties, and conductivity (Kruželák et al., 2020). Biodegradable variants may present sustainable options amid prevailing environmental pressures (Prabhu et al., 2023).

High filler concentrations may impair processing and physical–mechanical properties, while polymer composites generally appear to offer ease of processing and design flexibility (Kruželák et al., 2020). Structurally, 3D architectures or optimized filler aspect ratios in epoxy may enhance mechanical performance and shielding effectiveness (Zecchi et al., 2024). Micro- and macrostructure design, including filler morphology and distribution, may be pivotal for EMI optimization in high-power systems (Guan et al., 2024). Constituent selection (filler type, size, concentration) and the matrix may substantially influence shielding performance (Zecchi et al., 2024). Techniques such as additive manufacturing and electrospinning may enable precise filler alignment, which can tailor anisotropic shielding and mechanical properties (Ji et al., 2018; Niendorf & Raeymaekers, 2021).

1.5. Research Gap and Study Objectives

The primary objective of this investigation entails the development of innovative methodologies for integrating iron oxide nanoparticles into an epoxy matrix, thereby optimizing electromagnetic interference (EMI) shielding efficacy while preserving the mechanical robustness and biocompatibility of the resultant composites. Additionally, it will examine the effects of nanoparticle size, morphology, and loading on both EMI shielding performance and mechanical properties of the developed materials (Kumar et al., 2019),(Fallah et al., 2021). A detailed understanding of these microstructure-property correlations may prove essential for tailoring composites with superior attributes suited to targeted applications (Zecchi et al., 2024). The study will also assess the long-term durability and environmental implications of these composites, confirming their appropriateness for healthcare environments (Tochaikul & Moonkum, 2024). Moreover, it seeks to devise a systematic framework for linking the electromagnetic characteristics of these nanocomposites to their mechanical attributes, thereby advancing multifunctional materials for sophisticated medical apparatus (Zhang & Gu, 2022). In particular, it will mitigate the limitations of low electrical conductivity in metal oxide electrodes through hybrid nanostructures incorporating carbon-based materials to promote efficient ion transport and elevated capacitance (Alshaibani et al., 2024). This encompasses fabrication methods to achieve homogeneous dispersion of shielding particles, which is indispensable for maximizing attenuation and structural coherence (Tochaikul & Moonkum, 2024). Furthermore, the performance of the synthesized composites will be benchmarked against conventional standards, including lead sheets and legacy radiation shields, to evaluate their viability as substitutes (Tochaikul & Moonkum, 2024). These composites hold promise as lightweight, pliable alternatives to lead-based shields, especially for wearable safeguards and medical instrumentation exposed to gamma and X-ray radiation (Abdel-Kader et al., 2024; Govenkar et al., 2024). This pursuit appears warranted given lead's toxicity and weight, underscoring the need for lead-free, lightweight, economical options that curtail secondary Bremsstrahlung emission (Govenkar et al., 2024). The research will additionally probe the ramifications of gamma irradiation on the structural, optical, and electrical attributes of these composites, verifying their resilience under sustained radiation exposure (Naikwadi et al., 2022). Such appraisal may yield useful insights into the feasibility of these materials for multifaceted radiation shielding in medical contexts (Prabhu et al., 2022). These innovations may establish a category of lightweight hybrid composites exhibiting augmented mechanical strength and radiation attenuation (Khalil et al., 2024). Embedding high-Z constituents in polymeric matrices may enhance gamma attenuation via heightened photon interaction probabilities (Alabsy et al., 2024). Furthermore, nanoparticle incorporation fosters uniform radiation interaction attributable to their expansive surface area and small dimensions, thereby amplifying shielding proficiency (Elsafi et al., 2024). This paradigm also enables multilayered architectures, amalgamating disparate materials to refine attenuation across diverse radiation spectra (Al-Saleh et al., 2023). Evaluations will encompass photon attenuation capacity, mechanical attributes, and stability under emulated clinical conditions (Prabhu et al., 2022). This endeavor addresses the escalating need for sophisticated radiation-protective materials in medicine—namely, those which are lightweight, resilient, and environmentally compatible (Abdel-Kader et al., 2024; Alshipli et al., 2023). By offering a sustainable, high-efficacy paradigm for medical radiation shielding, particularly for diagnostic X-rays below 150 kV and gamma rays, it bridges existing gaps in shielding technology (Mehrra et al., 2021). The potential integration of these composites into wearable shields will be explored, enhancing safety and ergonomics for radiation-exposed medical staff (Wu et al., 2024). The investigation will further conceptualize adaptive shielding materials that dynamically modulate attenuation according to environmental radiation profiles. This holistic strategy may advance radiation protection via a robust framework for devising, appraising, and deploying next-generation shields in healthcare. Nanoparticle size and dispersion optimization will be paramount, as finer, uniformly distributed particulates markedly elevate

attenuation via augmented surface area and radiation interaction (Tochaikul & Moonkum, 2024). Microstructural scrutiny will validate homogeneity and detect agglomeration risks that could impair shielding (Mehrara et al., 2021). Ultimately, compatibility with extant medical systems and clinical longevity will be gauged to expedite bench-to-bedside translation, bolstering radiation safety for patients and practitioners (Al-Saleh et al., 2023). This endeavor may address the demand for potent, sustainable shielding vis-à-vis the recalcitrant nature of conventional synthetics (Prabhu et al., 2023), aligning with burgeoning imperatives for eco-solutions across industries (Tochaikul & Moonkum, 2024).

2. Literature Review

2.1. Previous Work on Ionizing Electromagnetic Radiation Shielding Materials

Recent research increasingly emphasizes the development of lightweight, flexible, and high-performance shielding materials (Zhang & Gu, 2022). Specifically, the incorporation of nanoparticles into shielding matrices may significantly enhance electromagnetic interference shielding effectiveness, which suggests these materials could be viable alternatives to conventional shielding systems (Zecchi et al., 2024). Concurrently, shielding technology has shifted from monolithic attenuators toward multilayered hybrid architectures, which are engineered to provide broader and more robust protection across diverse radiation and electromagnetic spectra (Al-Saleh et al., 2023; Prabhu et al., 2023). This transition reflects a growing demand for advanced materials that reconcile superior shielding performance with flexibility, reduced weight, and multifunctional capabilities (Gouda et al., 2024; Sushmita et al., 2020).The incorporation of hybrid fillers, including combinations of CaCO3, Bi2O3, and WO3, has exhibited substantial promise in augmenting radiation shielding efficacy by harnessing the complementary attributes of each constituent to optimize absorption (Tochaikul & Moonkum, 2024). Uniform dispersion of these nanoparticles within diverse matrices, such as epoxy resin, polyethylene, or polyvinyl chloride, appears pivotal for the preservation of structural integrity and functional performance of the composites (Tochaikul & Moonkum, 2024). Contemporary developments appear to prioritize polymer nanocomposites as potential lead-free shielding alternatives for medical and industrial uses, integrating fillers like cement, iron oxide, aluminum oxide, and bismuth oxide into low-density polyethylene matrices (Baamer et al., 2024). This encompasses a thorough analysis of how variables such as filler loading, particle dimensions, and dispersion uniformity modulate shielding performance against diverse ionizing radiation modalities (El-Khatib et al., 2023; Prabhu et al., 2023). The review also scrutinizes the mechanical characteristics and enduring stability of these composites—essential for deployment in rigorous settings—juxtaposed against the drawbacks of traditional lead shields, notably their inflexibility and toxicity (Govenkar et al., 2024; Zecchi et al., 2024). Furthermore, it addresses the ecological footprint and recyclability of these innovative materials, benchmarked via lifecycle assessments against conventional counterparts (Lopresti et al., 2020). This evaluation may underscore the need for pioneering shielding paradigms that harmonize efficacy with sustainability (More et al., 2021; Prabhu et al., 2023). Such eco-friendly composites, blending organic and inorganic elements, can be precisely engineered to modulate absorption and reflection mechanisms, thereby refining performance while curtailing environmental repercussions (Zecchi et al., 2024). This entails investigating high-atomic-number additives like barium sulfate, tungsten oxide, bismuth oxide, or lanthanum oxide, renowned for markedly elevating ionizing radiation attenuation owing to their elevated density and atomic mass (Tochaikul & Moonkum, 2024). These sophisticated nanocomposites, frequently leveraging nanoparticles, manifest amplified attenuation and superior dispersibility relative to micro-sized counterparts, culminating in heightened radiation interaction efficiency (Mahmoudian et al., 2023). For instance, bismuth oxide augmentation in low-density polyethylene may enhance shielding proficiency, curtailing the mean free path vis-à-vis pristine low-density polyethylene (LDPE) (Alshahri et al., 2021; Baamer et al., 2024). This superior attenuation arises from bismuth's elevated atomic number, which amplifies photoelectric absorption and Compton scattering probabilities, thereby diminishing X-ray and gamma-ray transmittance (Alshahri et al., 2021; Gharissah et al., 2022). Iron oxide, leveraging its magnetic attributes and substantial density, affords efficacious shielding against specific electromagnetic radiation spectra, especially elevated frequencies (Fallah et al., 2021). Deeper inquiries into its embedding within polymeric hosts reveal multifaceted utility, encompassing radiation attenuation, magnetic shielding, and bolstered mechanical resilience (Khalil et al., 2024). Employing polymers as matrices imparts flexibility, reduced mass, and facile processability, mitigating the constraints of standard metallic shields (Zecchi et al., 2024). The inherent traits of polymers—low density and adaptability to intricate geometries—position them as versatile for radiation shielding across sectors like aerospace and biomedicine (More et al., 2021). Epoxy resin integration with assorted fillers has been probed for its substantial mechanical robustness and chemical resilience, rendering it optimal for durable shielding composites (Tochaikul & Moonkum, 2024). Fabrication of epoxy-derived composites necessitates meticulous attention to filler dispersion and interfacial bonding, as these critically govern shielding potency and mechanical coherence (Saiyad et al., 2013). Bismuth trioxide, prized for its density and atomic number, is routinely embedded in polymer matrices as a potent gamma-ray attenuator (El-Khatib et al., 2022). Polymer composites fortified with non-lead, high-atomic-number inorganic fillers may represent promising radioprotective approaches (Muthamma et al., 2021). These exploit elements like barium to surpass conventional concrete or leaded glass in select scenarios (Govenkar et al., 2024). High-density polyethylene amalgamation with metal oxides such as cerium, tungsten, and erbium has propelled lightweight, oxidation-resistant shields (Alanazi et al., 2024). The adaptability of bismuth oxide- and tungsten-infused polymer composites facilitates bespoke configurations that attenuate broad radiation continua while upholding flexibility and minimal weight (Almurayshid et al., 2021; El-Khatib et al., 2019). Iron oxide incorporation into epoxy systems heralds advanced shielding materials with fortified mechanical attributes and attenuation prowess, attributable to iron's high atomic number and density for gamma and X-ray mitigation (Alshahri et al., 2021). Optimization of iron oxide nanoparticle concentration and morphology within the matrix maximizes shielding without undermining structural fidelity or manufacturability (Fallah et al., 2021). Extending beyond iron oxide, gadolinium oxide in epoxy resins evinces pronounced gamma-ray shielding augmentation, with sustained mechanical integrity under protracted irradiation (Li et al., 2017). Analogously, tungsten or gadolinium oxide powders profoundly enhance photon shielding in polymers, particularly for X-rays, via intensified photoelectric engagements in high-atomic-number media (Hanson et al., 2024). These composites may provide lead-free, lightweight, low-toxicity alternatives, especially for beta emitters where Perspex or aluminum supersedes lead to suppress bremsstrahlung (Govenkar et al., 2024).

Material/Composite Type	Matrix	Key Fillers/Additives	Primary Shielding & Functional Mechanisms
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Iron Oxide/Epoxy Nanocomposites	Epoxy Resin	Iron oxide nanoparticles (Fe_3O_4 , Fe_2O_3)	Magnetic loss, eddy current losses, microwave absorption, and gamma-ray attenuation.
Hybrid Carbon-Magnetic Systems	Epoxy/ABS	Graphene nanoparticles (GNPs), Carbon Nanotubes (CNTs), Magnetite	Dual dielectric and magnetic loss synergy, extended absorption bandwidth, and multiple internal reflections.
Lead-Free Medical Shielding	EPDM/ Low Density Polyethylene	Bismuth oxide (Bi_2O_3), Tungsten oxide (WO_3), Barium sulfate	High-Z photon interaction cross-sections, enhanced X-ray and gamma-ray attenuation.

Table 1: Comparison of Composite Materials and Fillers for Radiation/EMI Shielding

While lead offers excellent shielding properties, its toxicity may warrant exploration of alternative materials for medical applications (Abushahla & Arslan, 2025). The fundamental aim of radiation protection in healthcare settings is to prevent deterministic effects and reduce the risk of stochastic effects on medical care workers (Govenkar et al., 2024). This involves careful consideration of material choice, with an emphasis on balancing shielding effectiveness, material toxicity, and economic viability. For instance, the use of rubberized concrete, while presenting some compressive property limitations, may offer distinct advantages such as lower density, enhanced impact resistance, and improved sound insulation, making it a viable consideration for specific healthcare infrastructure components (Abdel-Kader et al., 2024). Conversely, while polymers offer good X-ray and gamma radiation protection with the addition of bismuth oxide (Bi_2O_3), their performance is highly dependent on composition and application techniques (Akbar et al., 2024). Furthermore, the development of lead-free polymer nanocomposites, particularly those incorporating Bi_2O_3 , appears to demonstrate high efficacy in X- and gamma-ray attenuation across a wide energy range, offering a safer and lighter alternative for healthcare applications (Alsaab & Zeghib, 2023). These lead-free alternatives are particularly important given the increasing awareness of lead toxicity and the momentum toward the adoption of more environmentally sustainable and safer materials in medical environments (Abushahla & Arslan, 2025). Furthermore, novel approaches involve leveraging advanced manufacturing techniques, such as 3D printing, to create customizable and intricate shielding geometries from these innovative composite materials, optimizing both performance and material utilization. This may enable the production of lightweight and flexible shielding, particularly advantageous in medical contexts where patient comfort and manoeuvrability are paramount (Arslonova et al., 2026). Such innovations in material science and manufacturing processes may be important for advancing radiation protection and may help ensure both efficacy and safety in diverse medical applications. (Wang et al., 2026) The impetus for developing these novel lead-free shielding solutions stems from the inherent drawbacks of traditional lead-based materials, which include their considerable weight, rigidity, and the significant environmental and health hazards associated with their toxicity (Safari et al., 2024; Wu et al., 2024). Consequently, there may be a need for new shielding materials to replace conventional lead-based ones, with polymer matrix composites emerging as promising candidates due to their flexibility, chemical stability, low weight, and low maintenance (Safari et al., 2024). These next-generation materials often leverage nanoparticles of bismuth oxide or tungsten, which may significantly enhance radiation shielding efficiency due to their larger surface-area-to-volume ratio, facilitating greater photon absorption compared to bulk materials (Elsafi et al., 2022). Beyond X-ray and gamma radiation, these advancements also extend to electromagnetic interference shielding, with polymer nanocomposites offering good conductivity, lower density, and higher corrosion resistance compared to traditional metal shields, making them suitable for sensitive electronic equipment in healthcare settings (Fallah et al., 2021). The development of advanced electromagnetic interference shielding composites, therefore, may contribute to safeguarding sensitive medical equipment and ensuring reliable operation within the increasingly complex electromagnetic environments of modern healthcare facilities (Prabhu et al., 2023). These sophisticated materials must also endure adverse environmental conditions, including temperature fluctuations, abrasion, and moisture, while adhering to stringent regulatory standards and cost-effectiveness criteria (Prabhu et al., 2023). Ultimately, the ongoing research into novel shielding materials aims to synthesize enhanced radiation protection with broader applicability, moving beyond traditional lead-based solutions (Aghamiri et al., 2011). For instance, iron oxide nanoparticles embedded in polymer matrices exhibit promising shielding capabilities against various radiation types while offering reduced toxicity compared to lead, aligning with the growing demand for safer alternatives (Khalil et al., 2024). Furthermore, the utilization of epoxy resin as a matrix for incorporating various shielding materials may facilitate the creation of composites with tunable properties for specific radiation protection requirements (Abbas et al., 2022).

2.2. The Implementation of Nanoparticles in Radiation Shielding Protocols

Incorporating magnetite and carbon black nanoparticles may manifest a marked improvement in the electromagnetic interference (EMI) shielding efficacy of polymer composites, thereby engendering enhanced reflective and absorptive losses against electromagnetic waves (Fallah et al., 2021). Similarly, polymer nanocomposites incorporating specific nanofillers, such as gadolinium oxide, may confer efficacious X-ray attenuation, alongside a concurrent enhancement in the mechanical and fracture toughness of the matrix (Sayyadi et al., 2021). Furthermore, nanotechnology advancements may facilitate meticulous control over nanoparticle dispersion and alignment in the polymer matrix, thereby refining the EMI shielding capabilities of these nanocomposites (Zecchi et al., 2024). Polymer nanocomposites, for instance, appear to be gaining traction as suitable lead-free materials for diagnostic X-ray shielding owing to their inherent tunability, which may be modified by varying the nanofiller type, nature, and concentration (Jayakumar et al., 2023). The integration of MXene nanosheets into polymer matrices, for example, appears to engender a significant enhancement in the electromagnetic interference shielding effectiveness of composite materials,

broadening their applicability in diverse technological contexts (Parajuli, 2024). Moreover, the elevated surface-area-to-volume ratio of nanoparticles, exemplified by bismuth, may substantially augment photoabsorption and radiation shielding performance in polymers, concurrently contributing to the enhancement of mechanical and electrical properties (Govenkar et al., 2024). The dimensions and morphology of these nanoparticles may critically influence radiation absorption efficiency, wherein smaller particles confer augmented surface-area-to-volume ratios and superior matrix dispersion, thereby culminating in optimized shielding capabilities (Tochaikul & Moonkum, 2024). For example, one-dimensional fillers like carbon nanotubes or graphene nanoplatelets may promote the formation of conductive networks that elevate electrical conductivity, thereby conferring exceptional EMI shielding capabilities (Zecchi et al., 2024). Nanoscale fillers, owing to their homogeneity and minimal agglomeration, may further

potentiate radiation attenuation through an enhancement of composite dispersion (El-Khatib et al., 2019). This homogeneous distribution may notably foster robust conductive pathways, which serves as a controllable attribute for the attainment of superior shielding (Prabhu et al., 2023). The inherent electrical conductivity and magnetic permeability of these fillers may fundamentally govern overall EMI shielding effectiveness, modulating reflective and absorptive losses (Zecchi et al., 2024). Additional enhancements in EMI shielding may be realized by hybridizing nanofillers, such as carbon-based materials with magnetic nanoparticles, thereby engendering synergistic effects that amplify shielding through conductive and magnetic loss pathways (Kruželák et al., 2020). This synergistic methodology may enable the engineering of advanced composites with customized electromagnetic absorption and reflection profiles, vital for averting secondary electromagnetic pollution (Yang et al., 2023). These hybrid nanocomposites may demonstrate superior electromagnetic wave absorption and reflection, which is attributable to integrated dielectric and magnetic losses, and is tunable via filler morphology and matrix distribution (Fallah et al., 2021). Notably, carbon-based nanofillers, including graphene and carbon nanotubes, may bolster EMI shielding through the augmentation of electrical conductivity and charge delocalization (Kruželák et al., 2020). In contrast, ferromagnetic nanoparticles like Fe_3O_4 may amplify magnetic losses, thereby extending the effective absorption bandwidth (Fallah et al., 2021). This synergy, therefore, appears to yield elevated EMI shielding effectiveness, rendering such composites apt for diverse shielding demands (Kruželák et al., 2020). The engineered segregated conductive networks in polymer composites, utilizing carbon nanotubes and graphene, may optimize EMI shielding through intensified internal reflections and absorption, thereby surpassing traditional uniform dispersion approaches (Ma et al., 2024). This refined nanofiller architecture and formulation may afford precise impedance matching, which facilitates maximal wave ingress and dissipation via internal reflections and absorption rather than surface reflection (Kruželák et al., 2020).

The influence of nanoparticle properties on electromagnetic interference (EMI) shielding effectiveness (SE) appears significant (Zecchi et al., 2024). For example, tailoring the aspect ratio and surface functionalization of graphene nanoplatelets or carbon nanotubes enhances their dispersibility and interfacial bonding within the polymer matrix, thereby improving electrical conductivity and electromagnetic interference shielding effectiveness (Kruželák et al., 2020). Moreover, the filler concentration, such as that of graphene nanoplatelets, appears to play a critical role; elevated loadings may typically yield superior shielding due to augmented electrical conductivity and frequency-dependent absorption (Chandra et al., 2023). Notably, epoxy composites incorporating 17 wt.% graphene nanoplatelets exhibited transmittance below 30% across the X-band, with a minimum of 15%, underscoring the strong link between filler loading and shielding efficacy (Zecchi et al., 2024). This elevated conductivity promotes a robust conductive network, facilitating electromagnetic energy dissipation via resistive losses and multiple internal reflections (Fallah et al., 2021). Additionally, the intrinsic electrical attributes of the polymer matrix and fillers—such as single-walled carbon nanotubes—coupled with their size and morphology, profoundly impact the composite's complex permittivity and conductivity (Kruželák et al., 2020). Thus, precise selection and optimization of these factors may be important for engineering composites with high EMI shielding performance. For instance, graphite-reinforced ultra-high molecular weight polyethylene achieved over 45 dB EMI shielding effectiveness in the X-band at just 7.05 vol.% graphite (Zecchi et al., 2024). This SE at low loadings may indicate the viability of lightweight, high-performance materials for aerospace and portable electronics. The distinctive morphology of graphene nanoplatelets, comprising 10–30 stacked graphene sheets, confers superior thermal and electrical properties, which may make them suitable for barrier functions at 2–5 wt.% in polymers (Kruželák et al., 2020). Their high aspect ratio fosters an interconnected conductive network at low percolation thresholds, markedly enhancing conductivity and EMI SE (Kruželák et al., 2020). Specifically, elevating graphene nanoplatelet content in acrylonitrile-butadiene-styrene nanocomposites from 3 to 15 wt.% boosted SE from 5.79 dB (ABS+GNP3) to 30.74 dB (ABS+GNP15) (Chandra et al., 2023). Such gains are amplified by techniques like partial dissolution, which yield segregated structures enabling SE exceeding 20 dB at only 1 wt.% graphene nanoplatelets (Yang et al., 2020). At comparable loadings, multi-walled carbon nanotubes outperform carbon nanofibers and high-structure carbon black in EMI SE, owing to their superior aspect ratio and conductivity (Kruželák et al., 2020). This suggests an important role of filler geometry and electrical properties in forming effective conductive networks for EMI shielding. Furthermore, hybrid acrylonitrile-butadiene-styrene nanocomposites with graphene nanoplatelets and carbon nanotubes displayed electrical conductivity of 179.2 S m^{-1} and thermal conductivity of $1.56 \text{ W m}^{-1} \text{ K}^{-1}$, yielding EMI SE >20 dB in the X-band (Kruželák et al., 2020). Collectively, these results suggest the importance of material choice, morphological engineering, and processing strategies in developing advanced polymer nanocomposites for EMI shielding (Kruželák et al., 2020). Prospective investigations should explore innovative fabrication methods, including 3D printing, to produce intricate geometries and functionally graded structures that optimize filler distribution for superior EMI shielding (Kruželák et al., 2020). These advances could yield lightweight solutions effective across wider electromagnetic spectra, meeting the rising need for robust protection in sophisticated electronics. Additionally, reduced graphene oxide prepared via the Hummers method in nanocomposites shows frequency-dependent EMI SE, attaining 22–26 dB in the X-band at 2.5 wt.% RGO (Kruželák et al., 2020). Likewise, combining magnetite nanoparticles with RGO in polymethyl methacrylate (PMMA) composites enhanced EMI SE to 29.3 dB using merely 0.5 vol.% magnetite and 1.1 vol.% RGO (Kruželák et al., 2020). Innovative strategies, such as dual nitrogen-sulfur doping in graphene-based materials, have also achieved outstanding EMI shielding via multilevel reflections and porous architectures (Elagib et al., 2023). Moreover, introducing structural defects in carbon nanotubes and functional groups strengthens polymer interactions, boosting shielding by facilitating electron transfer and electromagnetic-to-thermal energy conversion (Elagib et al., 2023). These modifications may enhance scattering and absorption, vital for EMI attenuation (Kruželák et al., 2020). Strategic filler dispersion and localization in polymer blends—e.g., hybrid nanoparticles in polyvinylidene fluoride (PVDF) phases—may further improve microwave attenuation (Kruželák et al., 2020). Nonetheless, fabricating EMI shielding materials with adequate mechanical integrity for scalable production via extrusion, compression, or injection molding may remain challenging (Chandra et al., 2023). Recent progress appears to have yielded polymer composites balancing mechanical robustness and shielding, often via diverse fillers. For example, polylactic acid/graphene nanocomposites reached a peak EMI SE of 15 dB at 8 GHz, dominated by reflection (Zecchi et al., 2024).

2.3. Iron Oxide Nanoparticles for Shielding

Iron oxide nanoparticles, particularly magnetite, appear to significantly enhance electromagnetic interference shielding through mechanisms such as magnetic loss and eddy current generation (Shukla, 2019). These magnetic losses may be especially effective in the gigahertz frequency range, where oscillating magnetic fields induce magnetic dipoles within the material, resulting in energy

dissipation (Yadav et al., 2020). The incorporation of iron oxide nanoparticles into polymer matrices may provide a viable approach for the development of lightweight, flexible EMI shielding materials with improved absorption capabilities, particularly when combined with conductive fillers like graphene or carbon nanotubes (Srivastava & Manna, 2022; Zecchi et al., 2024). For instance, epoxy resin nanocomposites incorporating magnetite and carbon black nanoparticles exhibited remarkable shielding effectiveness in the 8.2–12.4 GHz range (Fallah et al., 2021). These hybrid systems may leverage the complementary effects of magnetic absorption from iron oxide and electrical conductivity from carbon-based components to optimize EMI shielding performance (Abbasi et al., 2019; Ribadeneyra et al., 2014). Moreover, the concentration and morphology of iron oxide nanoparticles may critically influence their magnetic permeability and dielectric properties, thereby determining the overall shielding effectiveness of the composite (Zecchi et al., 2024). Specifically, optimizing the particle size and surface chemistry of iron oxide nanoparticles allows precise control over their magnetic anisotropy and saturation magnetization—essential parameters for enhancing magnetic loss mechanisms in EMI shielding applications (Roca et al., 2018). Such targeted modifications enable tailoring of the material's electromagnetic response to specific frequencies, thereby improving absorption and reflection losses for broadband shielding (Fallah et al., 2021). Research suggests, for example, that the integration of smaller iron nanoparticles into polymer composites may substantially increase absorption shielding efficiency, elevating the total EMI shielding effectiveness (Kruželák et al., 2020). This enhancement stems from increased surface area and interfacial polarization effects in nanoscale particles, which intensify interactions with electromagnetic waves and promote greater energy dissipation (Kruželák et al., 2020). Synergistic integration of iron oxide nanoparticles with conductive fillers, such as carbon nanotubes or graphene, may further amplify EMI shielding by boosting both dielectric and magnetic losses, resulting in expanded shielding bandwidths (Kruželák et al., 2020). The inherent advantages of iron oxide nanoparticles—including low cost, environmental compatibility, and tunable magnetism—suggest their potential for advanced EMI shielding materials (Yadav et al., 2020). Their versatility accommodates various synthesis routes, enabling precise control over physicochemical properties for specialized applications in complex electromagnetic environments (Ali et al., 2016). Furthermore, ternary nanocomposites comprising iron oxides, carbonaceous materials like polyaniline, and carbon nanotubes may demonstrate superior microwave absorption due to enhanced synergistic interactions (Ghashghaei et al., 2018). This is evidenced by studies showing size-dependent microwave absorption and EMI shielding improvements achieved through controlled particle size tuning of iron oxide nanoparticles (Yadav et al., 2020). Fine-tuning electromagnetic parameters in these composites, particularly via polyaniline addition, refines absorption characteristics and enables versatile EMI mitigation (Luo et al., 2017). Beyond straightforward incorporation, advanced nanocomposite architectures—such as core-shell structures or layered designs—optimize interfacial interactions and iron oxide dispersion, maximizing dielectric and magnetic losses across broad frequency ranges (Kruželák et al., 2020). These configurations, for example, promote enhanced multiple internal reflections and electromagnetic wave attenuation, significantly improving absorption (Liu et al., 2023). Notably, the damping parameter due to surface effects in nanoparticles can increase significantly, even by an order of magnitude compared to bulk material, influencing overall EMI shielding performance (Fallah et al., 2026).

These loss mechanisms may arise from the interplay between incident electromagnetic waves and magnetic dipoles, alongside free charge carriers within the nanoparticles, leading to energy dissipation through hysteresis loss, eddy current loss, and dielectric relaxation (Kruželák et al., 2020). Moreover, the combination of iron oxides with other materials, such as carbon nanotubes or various polymers, has been shown to improve the microwave attenuation properties by offering a better balance between electrical conductivity and magnetic susceptibility (Afzali et al., 2022). Concurrently, dielectric losses appear to be regulated by interfacial polarization, dipole relaxation, and conduction losses, which are substantially enhanced by defects, heterogeneous interfaces, and conductive networks within the nanocomposite (Keykavous-Amand & Peymanfar, 2021). Together, these mechanisms may form the fundamental basis of electromagnetic interference shielding effectiveness by converting incoming electromagnetic energy into thermal energy or other dissipated forms (Sushmita et al., 2020; Zecchi et al., 2024). The strategic incorporation of both dielectric and magnetic loss pathways in tailored nanocomposites offers a versatile approach to developing materials with broadband EMI shielding capabilities (Wang et al., 2022). Furthermore, maintaining conductive network continuity and uniform dispersion of magnetic nanoparticles may be important for maximizing magnetoelectric synergies, thereby enhancing shielding effectiveness and promoting absorption dominance (Liu et al., 2024). Effective material design may necessitate the balancing of heightened absorption with minimized reflection to reduce secondary electromagnetic pollution (Keykavous-Amand & Peymanfar, 2021). This balance presents challenges in applications requiring high transparency or flexibility, such as the inherent trade-off between optical transmittance and shielding effectiveness (Chen et al., 2024). Ultimately, the interaction among composition, morphology, and processing parameters may shape the overall EMI shielding performance, underscoring the necessity for comprehensive characterization and modeling (Fallah et al., 2021; Zecchi et al., 2024). This analysis may include assessing the influence of factors such as porosity, particle size distribution, and filler loading on dielectric and magnetic loss tangents—critical indicators of electromagnetic energy dissipation potential (Prasad et al., 2019). Additionally, examination of complex permittivity and permeability spectra, particularly their imaginary components, may be important for elucidating energy dissipation mechanisms and guiding the development of materials with superior absorption across diverse frequency bands (Chandra et al., 2023). These findings may facilitate precise tuning of material properties to achieve optimal electromagnetic attenuation, enabling advanced, adaptable shielding solutions (Maruthi et al., 2020). Consequently, ongoing research appears to prioritize sophisticated architectures and computational modeling to predict and optimize the complex electromagnetic responses of these nanocomposites, advancing their deployment in state-of-the-art shielding applications (Kruželák et al., 2020). Persistent challenges may encompass the creation of lightweight, flexible configurations without compromising shielding efficacy, coupled with ensuring long-term durability and environmental robustness across varied applications (Nan et al., 2023).

For example, synthesis techniques such as co-precipitation, thermal decomposition, and hydrothermal processes provide unique advantages in regulating particle size, morphology, and crystallinity, which profoundly affect the magnetic and dielectric responses of iron oxide nanoparticles to impinging electromagnetic waves. Specifically, co-precipitation appears to be valued for its simplicity and scalability, enabling the production of superparamagnetic nanoparticles with tunable sizes via meticulous pH and temperature control, thereby governing their magnetic loss properties (Blanco-Andujar et al., 2012). Thermal decomposition, by contrast, may afford precise manipulation of particle size distribution and crystallinity, resulting in highly monodisperse nanoparticles exhibiting superior magnetic characteristics suited for high-frequency absorption (Li et al., 2013). Hydrothermal synthesis appears to excel in

the generation of highly crystalline iron oxide nanoparticles with customized morphologies that markedly alter their dielectric permittivity and electromagnetic attenuation efficacy (Wu et al., 2008). Moreover, the selection of synthesis route substantially influences defect chemistry and surface modification of iron oxide nanoparticles, which are pivotal for amplifying interfacial polarization and fostering conductive pathways in the nanocomposite matrix, thus optimizing dielectric losses (Yang et al., 2022). Such meticulous tailoring of nanoparticle characteristics through optimized synthesis protocols may be important for enhancing the electromagnetic interference shielding performance of the resultant nanocomposites, facilitating targeted modulation of reflection and absorption contributions to suit specific applications (Zecchi et al., 2024). Additionally, innovative hybrid filler strategies integrating organic and inorganic constituents present a viable pathway to refine electrical conductivity and achieve lightweight designs, thereby augmenting shielding absorption while modulating reflection (Zecchi et al., 2024). Notably, ternary composites of MXene, graphene, and Fe_3O_4 may yield flexible films with exceptional absorption-dominant shielding, exploiting synergistic dielectric and magnetic loss mechanisms (Prabhu et al., 2023). Incorporating these multifunctional materials engenders an adjustable electromagnetic response, with impedance matching to free space optimized to prioritize absorption over reflection—crucial for mitigating secondary radiation in sensitive environments (Prabhu et al., 2023). Furthermore, activated carbon as a porous additive in composites induces multiple internal reflections, bolstering absorption and curtailing reflection to alleviate secondary pollution (Prabhu et al., 2023). This deliberate materials engineering, encompassing bespoke synthesis and hybrid fillers, may exemplify an integrated strategy for next-generation EMI shielding materials featuring preeminent absorption and subdued reflection, indispensable for sophisticated electronics (Liu et al., 2024; Yang et al., 2022; Zecchi et al., 2024). The efficacy of these graphene nanoplatelet-incorporated nanocomposites is amplified by their capacity to dissipate electromagnetic energy as heat via three-dimensional networks, favoring absorption over reflection at elevated loadings (Chandra et al., 2023). This multifaceted paradigm, integrating judicious material choices and sophisticated fabrication, yields EMI shields with refined impedance matching for superior energy dissipation and negligible re-emission (Ma et al., 2021). Hetero-interfaces in composites, exemplified by GnPs/SiC or MXene/Ni , intensify wave dissipation via augmented dielectric and magnetic losses, transducing incident energy into thermal energy (Ma et al., 2021). Such designs also enable lightweight, pliable shields vital for portable and wearable electronics, supplanting cumbersome conventional alternatives (Li et al., 2020). Judicious architecting of compositions and hierarchical structures may be necessary to harmonize mechanical pliancy, optical clarity, and environmental resilience—properties often mutually exclusive (Nepal et al., 2020). Consequently, persistent innovation in composite architectures and synthesis may remain important to surmount these hurdles and harness the potential of advanced EMI shielding for multifaceted technologies. Future research endeavors must therefore prioritize the development of scalable manufacturing processes that maintain the integrity of these intricate nanostructures while integrating them into robust, high-performance polymer matrices to ensure practical applicability in diverse engineering domains (Zhang et al., 2023). This encompasses imperatives in aerospace and telecommunications for low-mass, high-efficacy shields compliant with weight constraints (Zecchi et al., 2024). This requires a profound understanding of the interplay between material composition, microstructural design, and electromagnetic shielding mechanisms to inform the rational design of next-generation composites (Chhetri & Kuila, 2024). These advanced materials harness conductive or magnetic particulates to erect absorptive or reflective barriers, safeguarding personnel and electronics (Fallah et al., 2021; Zecchi et al., 2024). Beyond aerospace and defense, they ensure reliability in medical and automotive domains vulnerable to perturbations (Ma et al., 2024; Prabhu et al., 2023). With burgeoning flexible and wearable electronics, shields enduring deformation while sustaining efficacy are essential (Gong et al., 2024), spurring textile-integrated architectures with innate flexibility (Tao et al., 2024). Bidirectional freeze casting emerges as a potent method for lamellar-membrane shields with low filler demands and high performance (Yang et al., 2020). The integration of sustainable processes may address ecological drawbacks of ferrite-based absorbers (Samantara et al., 2024), propelling biodegradable polymers and bio-derived conductors for eco-compatible shields (Prabhu et al., 2023). Alternative fabrication routes like melt blending, solution casting, and in situ polymerization optimize filler dispersion and morphology for amplified shielding (Pai et al., 2020; Yang et al., 2023). Melt blending, solution casting, and electrospinning adeptly embed carbonaceous fillers (e.g., graphene, CNTs) into polymers, elevating conductivity and shielding while preserving mechanical properties. These enable filler alignment control, pivotal for shielding and integrity (Maruthi et al., 2020). In situ polymerization ensures uniform dispersion and interfacial bonding, bolstering performance (Maruthi et al., 2020). Nanotechnology advances refine nanoparticle orientation in matrices for peak shielding (Zecchi et al., 2024). Electrospinning fabricates nanoscale-fiber shields that are lightweight, flexible, and mechanically robust (Wei et al., 2021). Strategic nanofiller integration (graphene, carbon black, CNTs) enhances conductivity and shielding (Chandra et al., 2023; Wanasinghe et al., 2020). Organic fillers like carbon black excel in conductivity and lightness for flexible electronics (Zecchi et al., 2024). Co-precipitation, hydrothermal, and sol-gel methods scalably produce MXenes/metallics for superior composites (Kruželák et al., 2020). Conductive polymer composites with metals/oxides/ferrites/carbon span automotive-to-device applications (Kruželák et al., 2020). Hydrothermal and CVD yield ordered structures enhancing conductivity and absorption via morphology control (Prabhu et al., 2023). Sol-gel enables low-temperature homogeneous oxides/films with tunable properties for lightweight broadband shields (Zecchi et al., 2024). CVD/ALD deposit precise conductive layers minimizing reflection pollution (Chandra et al., 2023; Wei et al., 2024). ALD yields conformal coatings for intricate geometries, broadening applications (Wei et al., 2024). Surging demands for absorption-dominant, high-SE shields propel multi-mechanism hybrids (conductive/magnetic) for broadband efficacy (Kruželák et al., 2020; Prabhu et al., 2023).

2.4. Epoxy Resin Composites for Shielding

Epoxy resin composites may represent leading choices as matrices for high-performance electromagnetic interference shielding owing to their superior mechanical properties, thermal stability, and adhesiveness (Nambiar et al., 2025; Wang et al., 2022). Recent investigations have similarly examined hybrid filler systems that exploit the complementary characteristics of various materials, resulting in synergistic improvements in shielding performance across wide frequency ranges (Nan et al., 2023). These approaches frequently entail the inclusion of carbonaceous nanofillers, such as carbon nanotubes or graphene nanosheets, which form conductive pathways in the epoxy matrix to promote charge carrier mobility and augment absorption losses (Zheng et al., 2023). Furthermore, the incorporation of highly conductive carbonaceous materials, including graphite and graphene nanoplatelets, into epoxy matrices may substantially enhance electromagnetic interference shielding effectiveness, particularly in the X-band, via enhanced electrical conductivity and dominant absorption mechanisms (Fallah et al., 2021; Zecchi et al., 2024). Studies have also

explored three-dimensional architectures and tailored aspect ratios of carbon nanotubes in epoxy to optimize both mechanical attributes and outstanding EMI shielding capabilities (Zecchi et al., 2024). Developing lightweight polymer composites with conductive fillers may remain consequential for advancing shielding strategies, providing benefits in terms of flexibility and reduced weight compared to traditional metallic shields (Barani et al., 2020). The deliberate combination of dielectric and magnetic fillers in epoxy composites enhances shielding through complementary reflection and absorption effects, which are essential for broadband EMI suppression (Fallah et al., 2021; Kruželák et al., 2020). For example, epoxy composites incorporating multilayered graphene and metallic fillers like Fe_2O_3 demonstrate substantial potential for improving electromagnetic wave attenuation (Jaiswal et al., 2020). The advancement of epoxy-based composites via tailored filler synergies and architectural designs appears vital to meet the growing requirements for superior EMI shielding across varied technological sectors (Barani et al., 2020). (Barani et al., 2020; Prabhu et al., 2023) This advancement includes embedding sustainable, biodegradable fillers into epoxy matrices to mitigate the environmental impacts associated with synthetic polymers (Nambiar et al., 2025). These developments align with the increasing need for environmentally friendly materials and sustainable processing methods, especially in advanced EMI shielding contexts. (Prabhu et al., 2023; Samantara et al., 2024) Future refinements focus on improving filler dispersion and interfacial bonding to strengthen mechanical durability and long-term stability in eco-friendly EMI shielding materials (Wang et al., 2022). Such advancements may be instrumental in creating next-generation, high-efficacy, environmentally responsive electromagnetic shields that adhere to stringent industrial and sustainability standards (Nambiar et al., 2025).

Nanofillers such as carbon nanotubes and carbon black, when dispersed within epoxy matrices, may significantly enhance mechanical strength and durability, while also improving electrical conductivity crucial for electromagnetic interference (EMI) shielding applications (Deyab et al., 2024) (Fallah et al., 2021). However, achieving uniform dispersion of these nanoparticles within the epoxy matrix appears vital to ensure both structural integrity and optimal performance of the composite, as agglomeration can lead to reduced mechanical strength and diminished shielding effectiveness (Tochaikul & Moonkum, 2024). The incorporation of magnetite (Fe_3O_4) nanoparticles, for instance, can introduce magnetic properties that enhance the EMI shielding effectiveness by increasing the absorption of electromagnetic waves, in addition to contributing to mechanical reinforcement (Fallah et al., 2021) (Kruželák et al., 2020). This appears particularly relevant in applications requiring both structural robustness and efficient electromagnetic wave absorption, such as in aerospace and defense (Fallah et al., 2026). Furthermore, careful selection of nanoparticle geometry and aspect ratio can significantly influence the electrical percolation threshold and, consequently, the EMI shielding effectiveness of the composite (Abbasi et al., 2019). Moreover, the processing techniques employed during composite fabrication, such as extrusion or compression molding, can critically influence the final properties, including the dispersion of nanofillers and the overall EMI shielding effectiveness (Chandra et al., 2023). These methods, alongside considerations for interfacial adhesion between fillers and the epoxy matrix, may be important for tailoring composites to specific application requirements (Cipriotti et al., 2024). Understanding the intricate interplay between nanofiller characteristics, processing methods, and resulting composite properties appears to be of paramount importance for the development of next-generation EMI shielding materials (Cipriotti et al., 2024) (Mirzapour et al., 2024). The modulation of electromagnetic shielding effectiveness through precise micro- and macrostructure design may be critical for the optimization of performance across diverse applications (Guan et al., 2024). This includes the strategic use of hybrid filler systems, where the synergistic combination of magnetic and conductive nanoparticles can lead to enhanced broadband shielding performance (Kruželák et al., 2020). For example, incorporating graphene nanoplatelets with magnetic particles, such as those with Fe content, within polymer composites has been shown to significantly improve both electrical conductivity and magnetic permeability, thereby enhancing total shielding effectiveness, particularly in the X-band frequency range (Jin et al., 2018) (Kuester et al., 2017). Mechanical properties of epoxy composites, such as tensile strength and flexural modulus, can also be tailored through the careful selection and loading of nanofillers, which may help ensure that EMI shielding performance does not compromise structural integrity (Agnihotri et al., 2015) (Marra et al., 2018). Furthermore, the thermal stability of these composites can be significantly enhanced by the inclusion of specific nanoparticles, which may be crucial for applications exposed to elevated temperatures (Kruželák et al., 2020). The ability to control the particle size and distribution of fillers, such as natural graphite flakes, also appears to play a crucial role in the optimization of electromagnetic characteristics and shielding effectiveness, particularly in the X-band frequency range (Kruželák et al., 2020). Electrical properties of epoxy composites, such as permittivity and conductivity, appear to be directly influenced by the type, concentration, and dispersion of conductive fillers, which dictate the material's ability to reflect and absorb electromagnetic radiation (Guan et al., 2024) (Kruželák et al., 2020). The strategic incorporation of graphene nanoplatelets with high aspect ratios, for example, can significantly boost electrical conductivity, thereby improving the overall shielding effectiveness (Prabhu et al., 2023) (Marra et al., 2018). The electromagnetic interference shielding effectiveness of these composites appears not only dependent on the intrinsic properties of the two-dimensional fillers but also on the formation of three-dimensional interconnected networks, facilitating multiple absorption, reflection, and scattering of incoming electromagnetic waves (Wang et al., 2021).

Effective dispersion techniques, such as sonication and mechanical stirring, are essential to overcome van der Waals forces that cause nanoparticles to agglomerate, thereby maximizing their functional benefits within the composite (Anane-Fenin et al., 2019). Surface functionalization of nanoparticles with polymers or surfactants can further prevent re-agglomeration and improve compatibility with the matrix, leading to more homogeneous microstructures and superior performance characteristics (Hiremath et al., 2021). This uniformity appears to influence the material's mechanical properties by minimizing stress concentration points, and it may also enhance electrical and electromagnetic interference shielding effectiveness through the creation of continuous conductive pathways (Janjua et al., 2024) (Prabhu et al., 2023) (Zecchi et al., 2024). Moreover, the synergistic effects of combining different types of nanofillers, such as carbon nanotubes and graphene, can lead to enhanced dispersion stability and improved overall performance (Suherman et al., 2022). The incorporation of two-dimensional nanomaterials like MXenes may offer exceptional metallic conductivity and high stiffness, potentially enabling substantial enhancements in composite properties even at low loadings (Giménez et al., 2022). Furthermore, the careful selection of processing parameters, such as mixing speed and temperature, appears to play a critical role in the mitigation of agglomeration and the assurance of optimal distribution of nanofillers throughout the polymer matrix (Janjua et al., 2024). This meticulous control over processing conditions and material selection is vital for maximizing both the mechanical and electromagnetic performance of the resulting composites (Prabhu et al., 2023). These advancements facilitate the development of polymeric nanocomposites with tailored properties, enabling their use in sophisticated

EMI shielding applications where traditional materials fall short due to their inherent limitations, including weight and rigidity (Zecchi et al., 2024) (Colorado et al., 2023). The focus has now shifted to developing composite materials that offer a balance of high EMI shielding effectiveness, lightweight properties, and mechanical durability, often leveraging advancements in conductive polymer composites and foam structures (Prabhu et al., 2023) (Zecchi et al., 2024). This includes the development of green EMI shielding concepts where microwaves are predominantly absorbed rather than reflected or transmitted, often achieved through hierarchical nano-micro structures inspired by natural designs (Chandra et al., 2023). Nanoparticle agglomeration, a persistent challenge in nanocomposite fabrication, significantly impedes optimal performance by disrupting conductive pathways and interfacial interactions (Tamayo-Vegas et al., 2022). This phenomenon reduces the available surface area for charge carriers, thereby diminishing the material's overall electrical conductivity and electromagnetic wave absorption capabilities (Adnan et al., 2018). Consequently, advanced dispersion strategies and surface functionalization techniques may be critical to mitigating agglomeration, ensuring uniform distribution of nanofillers and maximizing the intrinsic properties of the composite material (Zecchi et al., 2024). The dimensionality of fillers, such as mono-dimensional structures, also significantly influences conductive pathway formation, thereby affecting electrical conductivity and EMI shielding performance (Zecchi et al., 2024). These factors may collectively underscore the complex interplay between material composition, morphology, and processing techniques in achieving high-performance electromagnetic shielding (Abbasi et al., 2019). To achieve uniform dispersion, advanced techniques such as functionalizing CNTs with suitable functional groups to enhance interactions with the host polymer, and utilizing pi-pi stacking for surface modification of MWCNT particles, are frequently employed (Elagib et al., 2023) (Kruželák et al., 2020). Furthermore, the selection of appropriate processing methods, such as compression molding or spin coating, can critically influence the dispersion state and subsequent EMI shielding effectiveness of carbon nanotube-polymer composites (Kruželák et al., 2020). This meticulous control over processing conditions and material selection may be vital for maximizing both the mechanical and electromagnetic performance of the resulting composites, particularly in the frequency range of 8.2–12.4 GHz (Fallah et al., 2021). Compression molding, for instance, has been shown to produce superior EMI shielding characteristics compared to injection molding by promoting a more random distribution of carbon nanotubes, which facilitates greater contact between adjacent conductive particles (Kruželák et al., 2020). This enhanced connectivity is crucial for establishing robust conductive networks, thereby optimizing the material's ability to attenuate electromagnetic radiation (Kruželák et al., 2020). Moreover, the thickness of the shielding material and the skin depth play crucial roles in determining the dominant shielding mechanism, whether reflection, absorption, or a combination thereof, particularly in highly conductive materials (Kruželák et al., 2020). Thus, an optimal balance between material thickness, electrical conductivity, and filler morphology is essential for tailoring the shielding effectiveness for specific applications (Fallah et al., 2021). The high aspect ratio and uniform distribution of carbon-based fillers, such as multi-walled carbon nanotubes, are critical for establishing rapid and efficient conductive networks within the polymer matrix (Zhao et al., 2019). This uniform distribution may facilitate effective electron transport and enhanced interfacial polarization, both of which are pivotal mechanisms for attenuating incident electromagnetic waves (Kruželák et al., 2020). Spin coating, however, may lead to less uniform dispersion of carbon nanotubes compared to compression molding, potentially limiting the overall shielding effectiveness (Sharma & Bose, 2021). Therefore, careful selection of the processing technique is paramount to achieving the desired electromagnetic shielding performance, especially when considering the specific application requirements and the inherent properties of the chosen conductive fillers (Sharma & Bose, 2021). The intricate interplay between filler concentration, dispersion quality, and network formation may dictate the overall electrical conductivity, which may correlate directly with the material's EMI shielding effectiveness through mechanisms like reflection and absorption (Kruželák et al., 2020). For highly conductive composites, absorption is often the predominant shielding mechanism, attributed to the material's ability to dissipate electromagnetic energy as heat (Das et al., 2020). Conversely, less conductive materials primarily rely on reflection to block electromagnetic waves, with the effectiveness largely dependent on impedance mismatch at the material's surface (Kruželák et al., 2020). The addition of magnetic nanoparticles, such as magnetite, can significantly enhance absorption loss, contributing to a higher mean absorption compared to composites lacking such components (Fallah et al., 2021).

2.5. Limitations in Contemporary Investigations Regarding Iron Oxide/Epoxy Composites for Ionizing Electromagnetic Radiation Shielding in Healthcare

While various studies have investigated polymer composites with fillers like bismuth, boron, and tungsten for ionizing radiation shielding, the potential of iron oxide nanoparticles within epoxy matrices for such applications appears, at present, to remain underexplored (Hamisu et al., 2023). Existing research primarily focuses on electromagnetic interference shielding in the radio frequency range, where iron oxide compounds like Fe₃O₄ have shown promise as cost-effective additives and electromagnetic absorbers (Bleija et al., 2024) (Zecchi et al., 2024). A recent study evaluated iron oxide/epoxy composites for gamma-ray attenuation and noted potential applications in medical facilities (Khalil et al., 2024). Consequently, recent evidence may support further investigation of ionizing radiation shielding capabilities of iron oxide/epoxy composites to ascertain their suitability as viable alternatives in healthcare applications (Khalil et al., 2024). Fe₃O₄ has been reported to absorb electromagnetic waves because of its magnetic properties, whereas Fe₂O₃/epoxy composites have demonstrated gamma-ray attenuation (Fallah et al., 2021; Khalil et al., 2024). Moreover, the adaptability of iron oxide nanoparticles in various forms, such as nano- and micro-particles, allows for tunable attenuation properties, which is crucial for optimizing shielding effectiveness against diverse ionizing radiation spectra (Khalil et al., 2024). The combination of iron oxide's attenuation properties with the mechanical strength of epoxy composites could lead to high-performance shielding materials (Elsafi et al., 2023; Khalil et al., 2024). Furthermore, the development of lightweight and flexible polymer-metal composites for radiation shielding is particularly relevant for medical applications, potentially offering alternatives to traditional lead-based shields due to their enhanced mechanical, physical, and radiation-shielding qualities, alongside improved affordability and durability (Abdel-Kader et al., 2024) (Elsafi et al., 2024). This may make them particularly attractive for scenarios requiring flexible and conformable shielding solutions (Alsaab & Zeghib, 2023) (Rabiei et al., 2024). This approach aligns with the growing demand for radiation shielding materials that are non-toxic, cost-effective, and environmentally benign, addressing the limitations of conventional lead-based shielding (Alsaab & Zeghib, 2023; Elsafi et al., 2024). Considering the increasing global concern regarding the deterministic and stochastic impacts of ionizing radiation, there may be a need for effective shielding technologies in medical and industrial settings to protect workers from escalating radiation levels (Elsafi et al., 2024). Such advancements may be critical for enhancing occupational safety and mitigating long-term health risks associated with

prolonged exposure to harmful radiation doses, particularly in diagnostic imaging and radiotherapy environments (Alanazi et al., 2024; Nambiar & Yeow, 2012). The escalating use of radiation in medicine further suggests the need for innovative shielding solutions that can be easily integrated into existing clinical workflows without compromising patient care or operational efficiency (Elsafi et al., 2024). This suggests the importance of exploring novel, high-performance, and sustainable shielding materials that can effectively attenuate ionizing radiation while also being explored for potential medical applications (Abdel-Kader et al., 2024).

The growing demand for lightweight, flexible shielding materials may have spurred the development of multifunctional systems capable of mitigating both electromagnetic interference and ionizing radiation (Flandy et al., 2026). By integrating these dual functions into a single material, such systems may reduce weight and operational complexity while providing protection for sensitive electronic and medical devices (Flandy et al., 2026). This integrated approach is particularly pertinent for critical sectors like aerospace and communication, where high EMI shielding performance and low density are paramount due to strict weight limitations (Zecchi et al., 2024). The inherent flexibility and customizability of polymer composites, combined with the tunable properties of iron oxide nanoparticles, allow for the design of application-specific shielding solutions that can conform to complex geometries, further expanding their utility in diverse settings (Qi et al., 2025). This comprehensive strategy may help meet the demand for advanced materials capable of mitigating various radiation hazards in a single, efficient solution, moving beyond the traditional limitations of single-purpose shielding (Wu et al., 2024). Furthermore, these novel composites could offer a sustainable alternative to traditional lead-based shielding materials, mitigating environmental and health concerns associated with lead toxicity while maintaining robust radiation protection (Abushahla & Arslan, 2025). This observation appears to align with the broader scientific objective regarding the development of lead-free shielding materials to address environmental disposal concerns, while simultaneously prioritizing the integration of efficient, lightweight, and flexible solutions (Alshipli et al., 2023). This paradigm shift towards flexible, lead-free shielding may prove crucial for medical personnel who require protective wearables that demonstrate efficacy and comfort during prolonged usage (Govenkar et al., 2024).

Moreover, the development of these advanced composites allows for the incorporation of nanomaterials, which may enhance shielding capabilities by providing superior absorption and attenuation properties in multi-layer designs (Al-Saleh et al., 2023). This development may ultimately contribute to a more sustainable and ergonomic solution for radiation protection, thereby addressing the inherent limitations of conventional materials such as lead (Govenkar et al., 2024).

3. Materials and Methods

3.1. Materials

The specification of all chemicals and materials, including iron precursors, epoxy resin, hardeners, and solvents, with their respective purity grades and suppliers, may support experimental reproducibility (Fallah et al., 2021; Prabhu et al., 2023). Additionally, comprehensive detailing of the precise chemical composition and purity of each constituent may improve the replicability of findings and facilitate rigorous comparative analysis across investigations. This meticulous documentation underscores its significance in elucidating the potential impact of material property variations upon the final composite's shielding efficacy and mechanical attributes. Furthermore, the specific grades and purity levels may be consequential because even minor impurities could alter the composite's electromagnetic or radiation-attenuation properties, necessitating a complete account of all constituents. The precise

characterization of these raw materials, encompassing their particle size distribution and morphological features, is additionally paramount for the accurate prediction of their interaction within the polymer matrix and the consequent microstructure of the composite. Such detailed material specification concurrently facilitates the accurate modeling and simulation of the composite's behavior under various radiation exposures, thereby affording insights into the optimization of material ratios and fabrication processes for superior shielding effectiveness. This granular approach to material selection and documentation may support the robustness and reliability of experimental outcomes, thus empowering subsequent researchers to precisely replicate and advance the presented findings. The materials employed in this study included ethylene propylene diene monomer (EPDM), characterized by an ethylene content of 54% and a density of 0.86 g/cm³, sourced from Arlanxco performance elastomers, Netherlands (Abdel-Kader et al., 2024). Moreover, waste rubber was integrated into the composites, obtained from an undisclosed local supplier, with a composition of 50% rubber and 50% textile fibers, thereby introducing a sustainable dimension to the material's formulation (Abdel-Kader et al., 2024). Zinc oxide, utilized as an activator, possessed a specific gravity ranging from 5.55 to 5.61, while stearic acid, with a melting point of 67–69 °C, served as an essential processing aid (Abdel-Kader et al., 2024). Polyvinylidene fluoride, specifically KYNAR 740 pellets with a specific gravity of 1.78 g/cm³ and a melting temperature of 168 °C, was procured from Arkema Inc., France, for use as a blend component (Salaeh, 2014). Other critical additives included tetramethyl thiuram disulfide as an accelerator and N-isopropyl-N'-phenyl-p-phenylenediamine as an antidegradant, both essential for optimizing the curing process and enhancing the long-term durability of the rubber compounds (Abdel-Kader et al., 2024). Sulfur, with a purity of 99.9%, was incorporated as the primary vulcanizing agent (Shafik et al., 2023). All other reagents, including various metal oxides (Al₂O₃, CuO, CdO, Gd₂O₃, or Bi₂O₃), were of analytical grade and used without further purification (Alabsy & Elzahr, 2023). For instance, azodicarbonamide, a chemical blowing agent with a gas yield of 220 mL/g, was obtained from Haihong Chemical, China, and zinc oxide powder from EL Nasr Chemical Co. (Farouk et al., 2020). Styrene-butadiene rubber, acquired via emulsion polymerization, was supplied by Synthos S.A., Poland; concurrently, other rubber mixture components, encompassing sulfur, zinc oxide, and stearic acid, were provided by BASF AG, Germany. Similarly, bismuth oxide with a density of 8.9 g/cm³ was investigated as a gamma photon attenuator due to its high atomic number (Govenkar et al., 2024). Conversely, natural rubber and acrylonitrile-butadiene rubber were utilized as the polymer matrices for some composites, with NR provided by the Rubber Research Institute of Vietnam and NBR (Europrene N 3345, acrylonitrile content 34%) sourced from Enichem Co., Italy (Elsayed et al., 2018). For specialized applications, additional components such as dioctyl phthalate were incorporated as a plasticizer to enhance material processability, while other formulations included tetramethylthiuram disulfide and 2-mercaptobenzothiazole as accelerators to optimize sulfur vulcanization kinetics (allah et al., 2017). Stearic acid, a common cure activator, was procured from Imperial Chemical Co., Ltd., Thailand, while zinc oxide, another cure activator, was supplied by Global Chemical Co., Ltd. (Hayeemasae et al., 2022). The integration of various metal oxide fillers within polymer matrices may yield improved radiation-shielding efficacy, with bismuth oxide and aluminum powder composites, in particular, exhibiting excellent mechanical properties and promising

radiation attenuation across the range of 140 keV to 511 keV (Govenkar et al., 2024). Nanocomposites, specifically those incorporating bismuth, may further enhance radiation-shielding properties compared to micro-composites, offering superior attenuation due to their increased surface area-to-volume ratio and improved filler dispersion (El-Khatib et al., 2024) (Govenkar et al., 2024). This enhanced performance underscores the potential for developing highly effective, lightweight, and flexible radiation shielding materials, particularly when considering non-toxic alternatives to traditional lead-based systems (Muthamma et al., 2021) (El-Khatib et al., 2019). For instance, sulfur-vulcanized natural rubber latex nanocomposites incorporating nano-Bi₂O₃ or nano-BaSO₄ have demonstrated enhanced X-ray shielding, with optimal filler content ranging from 95–140 phr due to the high atomic numbers and densities of bismuth and barium (Thumwong et al., 2022). Iron oxide nanoparticles, specifically, may be integrated into multi-layer shielding systems to further augment radiation absorption capabilities (Khalil et al., 2024). Moreover, the strategic incorporation of these nanoparticles within a polymer matrix frequently appears to significantly enhance the composite's overall mechanical integrity, thereby mitigating potential brittleness often associated with elevated filler loading in conventional shielding materials. Incorporation of iron oxide nanoparticles, for instance, provides a sustainable approach to enhancing radiation shielding while also improving thermal stability and mechanical strength (Prabhu et al., 2023). Iron precursors, such as iron oxides and iron salts, are amenable to synthesis for the fabrication of advanced shielding materials possessing tunable properties and enhanced cost-effectiveness. The strategic incorporation of such tailored iron-based components within polymer matrices may represent an advance in designing next-generation, high-performance radiation shielding materials for diverse applications (Mahmoudian et al., 2023). Epoxy resin types like bisphenol A and novolac are commonly utilized as matrices for radiation shielding composites due to their robust mechanical properties and excellent adhesion to various fillers, facilitating enhanced radiation attenuation performance (Tochaikul et al., 2025). FeCl₃, FeCl₂, and FeCl₃·6H₂O constitute additional iron-based compounds amenable to effective integration into polymer composites, thereby facilitating the further optimization of radiation shielding properties through the leverage of their distinct chemical structures and inherent attenuating capabilities. Furthermore, the optimization of filler dispersion and interfacial adhesion within these epoxy matrices appears paramount for the maximization of radiation shielding effectiveness and the preservation of mechanical integrity (Kalkan et al., 2023). The use of nano- and micro-particles, such as WO₃ and Gd₂O₃, within epoxy resin composites has been shown to significantly improve gamma-ray absorption and overall shielding capabilities (Cao et al., 2024). Various epoxy resins, including bisphenol-A based epoxy novolacs, can be combined with metallic oxide nanoparticles to achieve enhanced radiation shielding performance without compromising mechanical integrity (Qi et al., 2025). The incorporation of lead nanoparticles or alumina in epoxy/glass fiber composites has also been explored to achieve superior gamma radiation shielding properties and improved mechanical strength (Hussein et al., 2023). Moreover, the synergistic effect of combining micro- and nano-sized particles, such as tin oxide, within an epoxy matrix may increase linear attenuation coefficients across various energy ranges (Elsafi et al., 2024).

3.2. Synthesis of Iron Oxide Nanoparticles

The elucidation of the synthesis methodology necessitates the documentation of key parameters, including precursor concentration, reaction temperature, pH, and reaction time, which may collectively determine the final physicochemical profile (Prabhu et al., 2023). Crucially, the chosen synthesis method should be scalable for industrial applications while maintaining consistency in particle size distribution and purity, which are critical for reproducible shielding performance (Besenhard et al., 2020). Co-precipitation is a widely employed technique for synthesizing iron oxide nanoparticles due to its simplicity, cost-effectiveness, and ability to produce nanoparticles with straightforward experimental procedures, despite limited control over particle size, morphology, and crystallinity (Besenhard et al., 2020). This method typically involves the rapid addition of a base to an aqueous solution containing ferrous and ferric salts in a specific molar ratio, under an inert atmosphere to prevent oxidation (Blanco-Andujar et al., 2012). The precise control over these reaction conditions allows for tailoring the magnetic properties and surface characteristics of the resulting iron oxide nanoparticles, which are crucial for their integration into composite materials and their radiation shielding effectiveness (Aidos et al., 2025). The subsequent functionalization of these nanoparticles, often through surface coatings, can further enhance their compatibility with polymer matrices, thereby improving their dispersion and overall composite performance (Zecchi et al., 2024). This is particularly important for achieving uniform distribution within the polymer matrix, which is essential for maximizing radiation attenuation and maintaining the mechanical integrity of the composite (Tochaikul & Moonkum, 2024). The co-precipitation method, specifically, relies on adjusting the pH of the aqueous medium, which can influence both the size and stable dispersion of magnetite nanoparticles through electrostatic repulsion phenomena (Gutiérrez & Álvarez, 2018). While co-precipitation offers ease and cost-effectiveness for synthesizing iron oxide nanoparticles with irregular morphology and acceptable size control, alternative methods such as thermal decomposition yield highly monodisperse nanoparticles with tunable sizes, albeit at higher costs and with longer reaction times (Besenhard et al., 2020; Guimarães, 2017). The crystallinity of iron oxide nanoparticles synthesized via co-precipitation is often low, necessitating post-synthesis heat treatment to enhance their crystalline structure and optimize their properties (Singh et al., 2019). For example, Maurya et al. demonstrated that post-coating Fe₃O₄ with tetraethyl orthosilicate preserved the crystalline structure while slightly altering atomic composition, and dynamic light scattering showed a zeta potential similar to uncoated particles (Zhou et al., 2024). This preservation of crystalline structure and surface charge after coating may be crucial for maintaining the desired functionality and dispersion characteristics of the nanoparticles within composite systems (Cutrone et al., 2019). Such surface modifications not only improve colloidal stability but also facilitate robust interfacial bonding with the polymer matrix, which is crucial for the shielding performance of the resulting nanocomposite (Abbasi et al., 2019). The annealing temperature, for instance, significantly influences the phase composition and magnetic properties of iron oxide nanoparticles, directly impacting their suitability for electromagnetic interference shielding applications (Kruželák et al., 2020; Shukla, 2019). Similarly, the specific molar ratio of iron salts and the pH of the reaction medium are critical parameters that dictate the morphology, size, and aspect ratio of the resulting iron oxide nanoparticles, thereby influencing their electromagnetic properties and subsequent shielding efficacy (Zecchi et al., 2024). Hydrothermal synthesis, another method, typically produces highly crystalline nanoparticles with controlled morphologies under high temperature and pressure, offering an alternative for tailoring nanoparticle properties (Zecchi et al., 2024). This method enables the formation of diverse iron oxide polymorphs, each exhibiting distinct magnetic and electromagnetic characteristics crucial for optimizing shielding effectiveness (Prabhu et al., 2023). For example, Manna et al. synthesized Fe₃O₄@C core-shell nanostructures using a hydrothermal step followed by calcination, demonstrating the strong influence of these engineered fillers on electromagnetic measurements in the 2–8 GHz range, where higher

aniline ratios enhanced reflection while lower ratios increased absorption (Zecchi et al., 2024). These finely tuned properties are paramount for developing nanocomposites with optimized impedance matching and attenuation capabilities, crucial for broad-spectrum electromagnetic interference shielding applications (Kruželák et al., 2020). Other synthesis techniques such as sol-gel and microemulsion methods also offer distinct advantages in controlling particle size, morphology, and surface chemistry, which are critical for optimizing the performance of iron oxide nanoparticles in advanced shielding applications (Hiremath et al., 2021). The effectiveness of these polymeric nanocomposites for electromagnetic interference shielding is further influenced by factors such as surface area, porosity, aggregate structure, processing conditions, and filler loading level (Zecchi et al., 2024). Sol-gel synthesis, in particular, allows for the creation of intricate nanostructures with high surface areas, which can significantly enhance the interfacial polarization and ultimately the microwave absorption capabilities of the resulting composites (Keykavous-Amand & Peymanfar, 2021). Therefore, the precise control over the synthesis parameters across various methods may be indispensable for engineering iron oxide nanoparticles with tailored characteristics for specific electromagnetic shielding applications (Yadav et al., 2020). This intricate relationship between synthesis parameters and material properties underscores the importance of advanced characterization techniques to validate and optimize the performance of these sophisticated materials. The microemulsion method involves the utilization of surfactants to create thermodynamically stable oil-in-water or water-in-oil microemulsions, which may serve as nanoreactors for controlled nanoparticle growth, thereby facilitating the prevention of agglomeration (Bustamante-Torres et al., 2022). This method enables precise control over particle size and morphology, leading to enhanced electromagnetic interference shielding effectiveness due to improved dispersion and reduced reflection of electromagnetic waves within the composite material (Kruželák et al., 2020) (Chandra et al., 2023) (Prabhu et al., 2023). Moreover, the choice of solvent and polymerization conditions in the synthesis of hybrid materials, such as those incorporating polyaniline, significantly impacts the resulting morphology and, consequently, the microwave absorption properties (Lei et al., 2018). The composite fabrication method plays a crucial role in determining the final EMI shielding effectiveness, often involving techniques like extrusion, compression molding, and injection molding for mass production (Chandra et al., 2023). However, the uniform dispersion of fillers within the polymer matrix, which is vital for achieving optimal shielding effectiveness, remains a significant challenge (Prabhu et al., 2023). Parameters during synthesis, such as temperature, mixing speed, and pressure, must be meticulously controlled to overcome aggregation and achieve a homogeneous distribution of nanoparticles (Zecchi et al., 2024) (Prabhu et al., 2023). Precursor concentration, reaction temperature, pH, and reaction time are critical factors influencing the morphology, crystallinity, and ultimately, the electromagnetic properties of synthesized iron oxide nanoparticles. This precise control over synthesis parameters is crucial for tailoring the dielectric and magnetic losses, which govern the absorption mechanisms and overall electromagnetic interference (EMI) shielding effectiveness of the composite materials, particularly in high-frequency applications (Sparavigna, 2023). Further optimization of these parameters can lead to advanced nanocomposites exhibiting superior impedance matching and broader absorption bandwidths for next-generation electromagnetic interference shielding applications. Furthermore, the judicious selection of synthesis methods and parameters directly influences the type and extent of defects within the crystal lattice, which can dramatically alter the electromagnetic response of the nanoparticles through enhanced polarization mechanisms (Zecchi et al., 2024). These defects can act as trapping centers for charge carriers, leading to increased dielectric loss and improved absorption of electromagnetic radiation (Kruželák et al., 2020). Reaction temperature is another critical parameter, as it governs the reaction kinetics, particle growth rate, and phase purity of the synthesized iron oxide nanoparticles, thereby directly influencing their magnetic coercivity and saturation magnetization, both of which are vital for efficient microwave absorption (Zanotto et al., 2019). Moreover, controlling pH during synthesis significantly impacts particle aggregation and surface charge, which in turn affects the stability of nanoparticle dispersions and their compatibility with polymer matrices (Kruželák et al., 2020). Similarly, reaction time dictates the completeness of the reaction and the overall particle size, which, in conjunction with other parameters, influences the magnetic domain structure and subsequent microwave absorption characteristics (Prato et al., 2019). For instance, elevated reaction temperatures can lead to larger particle sizes, which have been correlated with a reduction in band gap energy and altered complex permittivity spectra, thereby impacting electromagnetic wave interactions (Zhao et al., 2021). For instance, the use of specific reducing agents can dictate the oxidation state of the iron, influencing the resulting magnetic phases (e.g., magnetite versus maghemite), while stabilizing agents are crucial for preventing agglomeration and maintaining a uniform particle size distribution, which is paramount for consistent electromagnetic response (Abdullah et al., 2023). Stabilizing agents play a pivotal role in dictating the surface chemistry of nanoparticles, thereby influencing their dispersibility within various matrices and their interaction with electromagnetic fields, which is critical for achieving optimal impedance matching and absorption (Yang et al., 2022). This multifaceted approach ensures that the synthesized iron oxide nanoparticles possess the desired electromagnetic properties, including optimal magnetic and dielectric losses, for effective EMI shielding applications (Chandra et al., 2023) (Fallah et al., 2021). Furthermore, post-synthesis treatments, such as annealing or surface functionalization, can fine-tune crystallographic defects and surface chemistry, further enhancing the electromagnetic absorption mechanisms within the material (Echeverría et al., 2021).

The specification of post-synthesis purification and drying procedures, including drying conditions, appears necessary to ensure material quality and consistency (Fallah et al., 2021). Typically, nanoparticles undergo rigorous washing with appropriate solvents such as acetone to remove residual impurities and unreacted precursors, a step that is fundamental for preventing aggregation and ensuring phase purity (Marins et al., 2018). This purification process may be consequential, as residual chemicals may alter the surface properties and colloidal stability of the nanoparticles, which are key factors in determining their electromagnetic response. Subsequently, the purified nanoparticles are often dried at controlled temperatures to eliminate any adsorbed moisture, a process critical for maintaining their magnetic and dielectric properties, as even trace amounts of water can alter their electromagnetic response (Fallah et al., 2021). For instance, magnetic nanoparticles often undergo a meticulous washing procedure with isopropanol, followed by magnetic separation, which is repeated until the suspension becomes transparent, signifying the complete removal of organic residues (Riahi et al., 2023). Afterward, the isolated nanoparticles are typically dried under vacuum or in an oven at controlled temperatures to remove any remaining solvent, a step that helps prevent agglomeration and preserve structural integrity (Solan et al., 2023). Such post-synthesis processing steps may prove pivotal for enhancing the material's bulk characteristics and preventing surface oxidation, a phenomenon which could be detrimental to electromagnetic shielding performance. For certain applications, the nanoparticles may be re-dispersed in hexane and then re-precipitated using ethanol, with centrifugation to achieve size-selective separation and remove surfactants that could negatively impact dispersion quality (Antonopoulos et al., 2021). These

extensive purifications and drying protocols may be essential for producing high-quality nanoparticles with consistent electromagnetic properties, which are critical for their reliable integration into advanced electromagnetic interference (EMI) shielding composites. The choice of washing solvent and drying method may influence the surface chemistry and structural integrity of the nanoparticles, which directly affects their performance in electromagnetic interference shielding. For example, the interfacial properties and surface chemistry of the nanoparticles can influence the interfacial polarization, which is a key mechanism for electromagnetic shielding (Ribadeneyra et al., 2014). Consequently, meticulous control over these post-synthesis stages may be important for achieving effective electromagnetic interference shielding performance by ensuring high purity, appropriate surface chemistry, and consistent material properties, thereby enhancing absorption and reflection losses. This meticulous control over the synthesis and post-synthesis parameters directly contributes to engineering iron oxide nanoparticles with tailored properties for optimal impedance matching and effective dissipation of electromagnetic energy. Ultimately, the optimized fabrication of iron oxide nanoparticles may support effective electromagnetic interference shielding performance through controlled dielectric and magnetic losses, enabling their integration into advanced composite materials.

3.3. Preparation of Iron Oxide/Epoxy Composites

The fabrication of composite materials, particularly via mixing and casting protocols, typically involves the dispersion of synthesized iron oxide nanoparticles within an epoxy resin matrix; this process, often utilizing mechanical mixing, sonication, or a combination thereof, may achieve a homogeneous distribution and prevent agglomeration (Domun et al., 2015). Subsequent curing of the epoxy resin then solidifies the composite, encapsulating the nanoparticles within the polymer matrix (Barrera et al., 2017). Mechanical mixing or magnetic stirring is often employed for a specified duration, typically 10–15 minutes, to facilitate the uniform dispersion of the nanoparticles within the epoxy matrix (Kaadhm et al., 2021). This method is then frequently followed by ultrasonication, typically for 10 minutes in an ice bath, to further deagglomerate the nanoparticles and ensure a more uniform distribution, which may be important for maximizing electromagnetic interference shielding effectiveness (Wang et al., 2022). Sonication may be particularly effective because the high-frequency sound waves generate cavitation bubbles that collapse, creating microjets that break apart nanoparticle clusters, thereby enhancing dispersion and preventing agglomeration within the matrix (Ávila-Orta et al., 2019). The mixing parameters, such as speed and duration, are often optimized to achieve adequate dispersion without prematurely curing the resin (Renteria et al., 2015). Following this, a hardener is introduced into the mixture, initiating the cross-linking reaction that solidifies the epoxy resin and permanently locks the dispersed nanoparticles in place (Naebe et al., 2014). The mixture is then typically degassed under vacuum to remove any entrapped air bubbles, which could compromise the mechanical and electromagnetic properties of the final composite (Naebe et al., 2014). This degassed mixture is then cast into molds and cured at elevated temperatures, often with a post-curing step, to achieve complete polymerization and optimal material properties (Barrera et al., 2017). For instance, melt mixing, a common technique for preparing nanocomposites, involves blending filler materials like Fe₃O₄ and carbon black powders with epoxy resin at controlled temperatures and speeds, followed by curing to solidify the mixture (Fallah et al., 2021). Alternative methods, such as the solution mixing technique, involve dissolving the polymer in a suitable solvent, dispersing the nanoparticles within this solution, and then removing the solvent to form the composite, often resulting in better dispersion at lower filler loadings (Barrera et al., 2017). To ensure optimal dispersion and prevent premature curing, the resin is often heated to reduce its viscosity before the introduction of nanofillers (Shah et al., 2023). Further enhancements in dispersion are often achieved through high-shear mixing, such as three-roll milling or planetary centrifugal mixing, which can promote significant exfoliation of nanofillers, improving interfacial bonding and overall composite properties (Agubra et al., 2013). Furthermore, the vacuum-assisted mixing process, utilizing equipment like a planetary centrifugal mixer, may be crucial for preventing air bubble formation and achieving a uniform distribution of nanoparticles, which can significantly enhance the electromagnetic shielding effectiveness of the composite (Pantano et al., 2018). The curing process, which can involve varying temperatures and durations, is also critical in determining the final mechanical and electromagnetic properties of the composite (Becker et al., 2003). Pre-curing of the nanocomposites at room temperature for 24 hours, followed by post-curing at an elevated temperature, such as 120 °C for 8 hours, may ensure complete polymerization and optimal material properties (Janjua et al., 2024). This systematic approach may facilitate the removal of trapped air during mixing, which may be important for preventing voids that could compromise the structural integrity and electromagnetic performance of the final composite (Kliem, 2018). In some protocols, pre-calculated amounts of carbon nanoparticles and magnetite nanoparticles are separately mixed with the epoxy prepolymer and curing agent via sonication to ensure homogeneous dispersion before casting and subsequent curing at ambient and elevated temperatures (Stavropoulos et al., 2022). These advanced fabrication methodologies underscore the importance of precise control over nanoparticle dispersion and matrix interaction for developing high-performance iron oxide/epoxy composites tailored for specific electromagnetic shielding applications. The complete evaporation of solvent, often ethanol, during the dispersion process is crucial to prevent residual solvents from compromising the structural integrity and electrical properties of the final epoxy composite (Cadenaro et al., 2008). The final step, curing, solidifies the resin, permanently embedding the nanoparticles and forming a robust composite material with enhanced electromagnetic interference shielding capabilities (Pantano et al., 2018).

Process Stage	Key Techniques/Methods	Operational Parameters & Objectives
Dispersion & Mixing	Mechanical stirring, Ultrasonication, High-shear / Three-roll milling	Duration: 10–15 min stirring followed by ~10 min ice-bath sonication to break down nanoparticle clusters. Objective: Overcome van der Waals forces, minimize agglomeration, and achieve uniform distribution.
Matrix Formulation	Solution mixing, Melt blending, In-situ polymerization	Solvent removal (e.g., complete evaporation of ethanol) to prevent structural and electrical flaws. Use of hardeners and degassing under vacuum to remove entrapped air bubbles.

Thermal Curing Protocols	Step-wise thermal management & Differential Scanning Calorimetry (DSC)	Initial low-temperature cure (e.g., room temp to 100°C–170°C) to manage viscosity.
		Post-curing at elevated temperatures (e.g., 120°C–220°C) to ensure full cross-linking density and optimize glass transition temperature (T_g).

Table 2: Overview of Fabrication, Processing, and Curing Parameters

The electromagnetic variables such as characteristic impedance and skin depth may depend substantially on the iron oxide concentration, directly influencing the microwave scattering parameters of the composite (Alegaonkar et al., 2021). The choice of iron oxide nanoparticle type (e.g., Fe3O4, γ -Fe2O3) and their morphological characteristics (e.g., spherical, rod-like) may also exert a substantial influence on the electromagnetic response, including both absorption and reflection losses, due to variations in magnetic permeability and dielectric permittivity (Zecchi et al., 2024). The interplay between increased magnetic loss from Fe3O4 and enhanced electrical loss, often supplemented by carbon allotropes, appears to contribute significantly to the overall shielding effectiveness, as evidenced by observations of an optimal balance at specific loading concentrations (Wang et al., 2022). Specific optimal ranges of nanoparticle loading are often determined experimentally, considering trade-offs between mechanical integrity, electromagnetic shielding effectiveness, and cost-effectiveness (Tao et al., 2024). For example, composites incorporating 9–15 wt.% graphene nanoparticles tend to exhibit enhanced electromagnetic wave attenuation, primarily through increased absorption rather than reflection, as observed in ABS+GNP15 nanocomposites (Chandra et al., 2023). This suggests that while a higher concentration of magnetic fillers like iron oxide can enhance absorption, the specific concentration may require careful optimization to achieve the desired balance between absorption and reflection mechanisms, especially in high-frequency applications (Wang et al., 2022) (Chandra et al., 2023). Ideal loading concentrations for iron oxide nanoparticles in epoxy composites tend to fall within a range that maximizes both magnetic and dielectric losses while maintaining processability and mechanical integrity (Fallah et al., 2021; Kaadhm et al., 2021). For instance, the enhancement of the aspect ratio of magnetite nanoparticles has been observed to increase their microwave attenuation coefficient, albeit sometimes at the expense of impedance matching (Zecchi et al., 2024). However, if their impedance matching can be improved, high-aspect-ratio nanorods can still produce microwave absorbers with excellent absorption properties (Zecchi et al., 2024). Furthermore, the careful control over the synthesis and dispersion of iron-based nanoparticles within polymer matrices may be important to the optimization of microwave absorption performance, as their size, morphology, and distribution directly impact the magnetic and dielectric properties of the resultant composite (Zheng et al., 2022).

Techniques such as high-shear mixing, sonication, and surfactant utilization are commonly employed to achieve homogeneous distribution of nanoparticles within the epoxy matrix (Schaefer et al., 2011). Ultrasonication, in particular, can effectively break down agglomerates and improve interfacial adhesion between the nanoparticles and the polymer matrix (Liu et al., 2001). The use of specific mixing protocols, including controlled shear rates and durations, may be considered crucial for preventing re-agglomeration and maintaining a stable dispersion throughout the composite fabrication process. The introduction of surface-modified nanoparticles or the use of dispersants can further mitigate agglomeration, promoting a more uniform distribution and enhancing the overall performance of the nanocomposite (Adnan et al., 2020). High-shear mixing, sonication, and magnetic stirring are frequently employed to achieve a homogeneous distribution of magnetic nanoparticles within the epoxy matrix, particularly considering the natural tendency of nanoparticles to aggregate due to high surface energy (Domun et al., 2015). The cluster-free distribution and interfacial interaction of nanoparticles with the polymer matrix may be critical factors that influence the effectiveness of these nanocomposites (Kumar et al., 2023). Surface functionalization of nanoparticles is another strategy employed to enhance dispersion by modifying their surface chemistry, thereby reducing inter-particle attraction and promoting compatibility with the polymer matrix (Barrera et al., 2017). For instance, the use of a shell material can enhance compatibility with the polymer matrix, improving overall dispersion and reducing agglomeration (Zecchi et al., 2024). Different industrial mixing methods, including mechanical stirring, ultrasound, and roller machines, have been explored to optimize the incorporation of nanoparticles into polymer resins, with combinations of these techniques often yielding superior dispersion (Barra et al., 2019). Optimized mixing processes may be essential for preventing the formation of agglomerates, which act as defect sites that can degrade the mechanical and electromagnetic properties of the composite (Alhabill et al., 2021). Therefore, selecting an appropriate mixing technique may prove pivotal for fabricating epoxy-based nanocomposites with enhanced mechanical characteristics and desired functional properties (Njuguna et al., 2007). To improve uniform dispersion, several mixing processes may be employed, including direct mixing, solution mixing, wet mixing, melt mixing, and in-situ polymerization, though solution mixing often poses challenges with large solvent volumes and environmental concerns (Ateş et al., 2020). Direct mixing methods such as melt mixing, miscible solvent mixing, and powder metallurgy techniques are effective for preparing polymer nanocomposites (Hiremath et al., 2021). Melt mixing is particularly advantageous for thermoplastic matrices, as it allows for the incorporation of fillers at elevated temperatures, facilitating better wetting and dispersion without the need for solvents (Ferrás et al., 2020). However, melt mixing can be challenging for thermosetting polymers like epoxy due to their cross-linking nature and high viscosity (Reddy, 2011). In such cases, blending routes, involving physical force and/or ultrasonication, are frequently employed to disperse nanoparticles within the resin (Adnan et al., 2018). The efficacy of these dispersion methods is often evaluated through quantitative imaging techniques, such as transmission electron microscopy and small-angle X-ray scattering, which provide insights into the nanoscale distribution and morphology of the nanoparticles within the polymer matrix (Prasad et al., 2020) (Feichtenschlager et al., 2020). Colloidal theory further elucidates how these dispersed particles interact within the liquid matrix, with particle size and surface charge significantly influencing agglomeration and distribution (Hernández et al., 2024). Miscible solvent mixing involves dissolving the polymer in a solvent, dispersing the nanoparticles within this solution, and then removing the solvent, which can lead to better particle distribution but necessitates careful solvent selection to avoid residual stresses and porosity (Wazalwar et al., 2021). Powder metallurgy techniques, while viable for some metal-matrix composites, are generally less applicable for epoxy-based nanocomposites due to the polymeric matrix's processing characteristics. The intrinsic methods, on the other hand, involve the formation of nanoparticles directly within the polymer matrix (Javadi et al., 2017). Solution mixing is a common approach for laboratory-scale production, where the polymer is dissolved in a suitable solvent, and then the filler is dispersed, followed by mixing at or above room temperature to obtain nanohybrid films through casting or precipitation (Patel et al., 2019) (Ateş et al., 2020). This method is characterized by its simplicity and low-temperature requirements, yet it demands careful solvent selection to ensure effective nanofiller dispersion and polymer dissolution (Vera et al., 2020). Wet mixing involves dispersing nanoparticles in a liquid medium before incorporation

into the polymer, which can reduce agglomeration and enhance interfacial interactions. However, the removal of the dispersing liquid can be challenging and may lead to residual solvent issues, impacting the final material properties. In-situ polymerization, alternatively, allows for the formation of nanoparticles directly within the monomer solution followed by polymerization, often yielding superior dispersion and interfacial bonding compared to ex-situ methods (Folorunso et al., 2024). This method may be particularly effective in achieving homogeneous dispersion of inorganic nanoparticles in various organic polymer matrices to fabricate hybrid polymer nanocomposites, especially when dealing with particles significantly smaller than the polymer chain length (Hiremath et al., 2021). Furthermore, the sol-gel method, a variant of in-situ nanoparticle preparation, offers advantages such as low processing temperatures and versatility in controlling particle morphology, which contributes to optimized polymer-nanoparticle interactions and avoids issues associated with preformed nanofillers (Barrera et al., 2017). This technique fosters superior control over particle size and inhibits aggregation by leveraging the polymer's functional groups as nucleation sites. These diverse fabrication strategies are thus tailored to specific material systems and desired properties, with careful consideration given to factors such as filler type, matrix chemistry, and end-use application (Shen et al., 2020) (Hiremath et al., 2021).

The implementation of a common curing protocol entails the heating of cast samples at specific temperatures for predetermined durations—such as an initial cure at 170°C for 1 hour, followed by post-cures at 200°C and 220°C for 2 hours each—to ensure complete cross-linking and optimal material properties (Ma et al., 2020). Another typical curing cycle involves an initial treatment at 80°C for 2 hours, followed by a post-cure at 125°C for 3 hours, allowing the samples to cool in the oven to room temperature before removal (Chaudhary et al., 2022). Such meticulous thermal management during the curing phase appears crucial for the achievement of desired mechanical strength and thermal stability within epoxy-based composites, particularly when incorporating fillers that influence the polymerization kinetics (Kang et al., 2025). The extent of curing can be assessed using differential scanning calorimetry, which monitors the enthalpy changes associated with the polymerization reaction, thereby indicating the degree of cure and potential for further cross-linking at elevated temperatures (Hiremath et al., 2014). The curing temperature and duration may also significantly influence the composite's glass transition temperature; higher temperatures and extended durations typically lead to an increased glass transition temperature, reflecting the formation of a more complete cross-linked network (Kang et al., 2025). Moreover, a step-wise curing profile, involving a low-temperature initial cure to increase viscosity followed by a high-temperature cure, can mitigate nanoparticle precipitation and enhance interdiffusion for improved adhesion (Daelemans et al., 2019; Tseng & Chang, 2024). Similarly, the inclusion of nanoparticles can alter the curing behavior of epoxy resins by inducing steric hindrance or affecting reaction rates, thereby necessitating adjustments to standard curing protocols to ensure optimal network formation and prevent adverse effects on composite properties (Hiremath et al., 2021). For instance, pre-curing at 100°C and 2 MPa for 1 hour, followed by post-curing at 120°C for 1 hour and 150°C for 6 hours, has been shown to yield well-cured epoxy resin composites (Song et al., 2024). These curing protocols are often informed by preliminary calorimetric studies using techniques like differential scanning calorimetry to identify optimal temperatures for complete crosslinking without decomposition, thereby maximizing the glass transition temperature (Dinu & Mija, 2020). This meticulous approach may help ensure that the epoxy resin achieves its maximum potential mechanical properties and thermal stability for its intended application. For example, a typical resin can achieve a glass transition temperature of 109°C after being thermopressed at 80°C under optimal curing and post-curing conditions, making it suitable for demanding in-service applications (Cadu et al., 2018). The glass transition values can also be compared with predictions from established models to validate the curing protocol and confirm near-ideal molecular network structures (Delannoy et al., 2022). Furthermore, the integration of nanoparticles within the epoxy matrix can necessitate an individualized optimization of the curing schedule, as their presence may influence the reaction kinetics and the ultimate crosslinking density (Kumar et al., 2023). High temperatures, for example, can accelerate the curing process of epoxy adhesives, leading to a higher glass transition temperature, as demonstrated by their application in gradient anchorage methods for prestressing fiber-reinforced polymer strips (Cruz et al., 2021). The mechanical and thermomechanical properties of the resulting resin may also be significantly influenced by the curing temperature and duration, with higher temperatures leading to an extended cross-linking process and stronger polymer networks (Lascano et al., 2019). Post-curing, in particular, may be critical to enhancing strength, elevating the glass transition temperature, and mitigating residual stresses within thermoset systems (Moller et al., 2020). This is particularly true for adhesive systems, where a proper post-cure schedule can significantly improve the glass transition temperature and overall mechanical performance (Chataigner et al., 2018). Additionally, post-curing at elevated temperatures may facilitate the formation of ether crosslinks and can induce backbone dehydration, further enhancing the material's thermal and mechanical properties (Moller et al., 2020). This also allows for the achievement of a more complete cure, especially when the initial curing process is stopped prematurely, thereby improving the long-term durability and performance of the epoxy composites (Lahouar et al., 2017). Curing epoxy resin with iron oxide can necessitate specific adjustments to the curing protocol, as the nanoparticles might influence the epoxy's reaction kinetics and the final properties of the composite (Sangermano et al., 2007). For instance, studies suggest that curing for 12 hours at 180°C may yield a complete epoxy cure, while excessive curing temperatures can lead to degradation, highlighting the importance of optimizing cure conditions to maintain mechanical integrity (Hoyt et al., 2023; Tsapatsaris et al., 2024). Similarly, the integration of magnetocaloric nanoparticles within an epoxy matrix can facilitate remote, wireless curing through alternating magnetic fields, providing an energy-efficient and on-demand adhesion mechanism (Chaudhary et al., 2020). This magnetic curing approach allows for precise control over the curing profile, which is particularly beneficial for complex geometries or temperature-sensitive substrates, minimizing thermal stress and optimizing the final material properties (Chaudhary et al., 2020). Such innovative curing methods are especially advantageous when considering the incorporation of thermally conductive nanoparticles like Fe₃O₄, which can introduce thermo-oxidative degradation under cyclical heating if not properly managed (Hiremath et al., 2021). Therefore, the development of sophisticated curing methodologies, including those utilizing magnetic fields, may represent an important advancement in tailoring the thermomechanical properties and long-term stability of nanoparticle-reinforced epoxy composites (Yin et al., 2024). The presence of Fe₃O₄ nanoparticles, commonly used as nanofillers, can significantly impact the curing process and the ultimate properties of epoxy resins, necessitating careful consideration of their influence on polymerization kinetics and cross-linking density (Jouyandeh et al., 2022). Specifically, the partial substitution of Fe²⁺ sites by Ni²⁺ cations in NiXFe₃-XO₄ nanoparticles has been confirmed to influence the curing potential of epoxy, as demonstrated through various characterization techniques (Jouyandeh et al., 2019).

3.4. Characterization of Composites

3.4.1. Structural and Morphological Characterization

The utilization of X-ray diffraction (XRD) facilitates the confirmation of the crystalline structure, phase purity, crystallite size, and incorporation of iron oxide nanoparticles within the composite (Fallah et al., 2021). The interaction between nanoparticles and the epoxy matrix can also be investigated using X-ray diffraction, revealing changes in the polymer's crystalline or amorphous regions due to filler incorporation (Bello et al., 2018). This technique may elucidate how nanoparticles could disrupt or enhance the polymer's inherent order, thereby influencing the composite's macroscopic properties (Velmurugan et al., 2023). Furthermore, XRD can identify any new phases formed during composite fabrication or curing, which could indicate chemical reactions or phase segregation within the material (Bello et al., 2018). For instance, the modification of Fe₃O₄ with cobalt and ethylenediaminetetraacetic acid influences its crystalline and phase structure, detectable by X-ray diffraction (Jouyandeh et al., 2019). Additionally, X-ray diffraction can assess the degree of exfoliation and dispersion of layered nanofillers, such as graphene oxide or polyhedral oligomeric silsesquioxane, within the epoxy matrix, which may exert a significant influence upon the mechanical and thermal properties of the resulting nanocomposite (Wazalwar et al., 2021). Moreover, the analysis of peak broadening in XRD patterns can provide information on crystallite size and lattice strain, offering insights into potential changes in the nanoparticle's internal structure upon incorporation into the polymer matrix (Kumar et al., 2019). Morphological characteristics of fracture surfaces, observed via scanning electron microscopy, can further elucidate the distribution and dispersion of nanofillers within the epoxy matrix, providing insights into fracture toughness and failure mechanisms (Domun et al., 2015). Similarly, elemental mapping through energy-dispersive X-ray spectroscopy may verify the homogeneous distribution of nanoparticles and the absence of significant agglomeration within the epoxy matrix, which may be associated with enhanced mechanical performance (Jlassi et al., 2018). These microscopic evaluations may complement macroscopic property measurements by providing direct visual evidence of the filler's role in influencing crack propagation and overall material integrity. The use of scanning electron microscopy following flexural tests can reveal smooth fracture surfaces indicative of brittle failure or plastic deformation, depending on the epoxy-rich regions and the presence of reinforcing nanosheets (Janjua et al., 2024). Furthermore, Small-Angle X-ray Scattering can provide valuable information about the distribution quality and structural morphology of nanoparticles within the composite, particularly useful for understanding the dispersion of inorganic nanoparticles in organic matrices (Feichtenschlager et al., 2020). This technique appears especially effective for the evaluation of the degree of agglomeration and the interparticle distances, which are critical factors influencing the mechanical reinforcement provided by the nanoparticles (Feichtenschlager et al., 2020). This detailed structural and morphological characterization appears crucial for the establishment of direct correlations between nanoparticle dispersion, interfacial adhesion, and the resulting bulk mechanical and thermal properties of the epoxy nanocomposites. Moreover, the examination of fractured surfaces using scanning electron microscopy can reveal the effectiveness of filler dispersion and the nature of the interfacial adhesion, which are critical determinants of the composite's mechanical performance (Adarmanabadi et al., 2021).

Characterization Technique	Target Property Evaluated	Key Insights / Findings
X-Ray Diffraction (XRD)	Crystalline structure, phase purity, and crystallite size	Confirms phase purity of iron oxide nanoparticles and evaluates disruptions or shifts in the polymer's crystalline/amorphous regions.
Scanning Electron Microscopy (SEM)	Surface morphology, dispersion quality, and fracture behavior	Visualizes filler dispersion, agglomeration risks, crack-pinning phenomena, and transitions between brittle and ductile failure modes.
Energy-Dispersive X-Ray Spectroscopy (EDS)	Elemental mapping	Verifies homogeneous distribution of elements (such as iron) across the composite matrix without significant clustering.

Table 3: Analytical Characterization Methods for Nanocomposites

Scanning Electron Microscopy is widely employed to analyze the cross-sectional area and the dispersibility of nanofillers within the matrix, generating high-magnification images that reveal critical details about the filler distribution and any agglomeration (Albozahid & Mateab, 2021; Tiwari et al., 2020). This methodology may prove particularly valuable for the observation of toughening mechanisms in nanofiber-reinforced epoxies and the analysis of fractured surfaces in nanocomposites following mechanical testing, thereby elucidating failure modes (Daelemans et al., 2020) (Janjua et al., 2024). This technique also allows for the assessment of interphase quality, as either excessively thin or thick interphases around nanoparticles can negatively impact the tensile strength of the composite material (Hiremath et al., 2021). In particular, scanning electron microscopy might highlight features such as crack pinning, indicative of robust nanoparticle-matrix interactions, or the presence of circular entities corresponding to individual nanoparticles, offering direct evidence of their distribution and size within the composite (Alhabill et al., 2018). Furthermore, SEM images of fracture surfaces may reveal microcracking and crack pinning, which are critical mechanisms contributing to enhanced fracture toughness in nanoparticle-reinforced epoxy systems (Boesl et al., 2011). Additionally, SEM can distinguish between ductile and brittle fracture surfaces, providing insights into the energy absorption capabilities and overall toughness of the material (Gharieh & Dorraji, 2021). Moreover, SEM, in conjunction with energy-dispersive X-ray spectroscopy, enables elemental mapping, verifying the homogeneous distribution of nanoparticles and the absence of significant agglomeration, which correlates directly with enhanced mechanical performance (Sahraeeazartamar et al., 2023). The size and density of these nanoparticles are crucial, as a reduction in both may lead to an expansion of the interfacial area, thereby enhancing the overall mechanical properties of the polymer nanocomposites (Hiremath et al., 2021). Observation of fracture surfaces via SEM can further differentiate between brittle failure, characterized by smooth crack propagation, and tougher fracture modes, where hackle and river lines indicate more tortuous crack paths influenced by nanoparticle interaction (Ogah et al., 2023). This detailed visual analysis aids in correlating microscopic features with bulk material properties, offering critical insights into the toughening mechanisms at play within the composite system (Adhikari & Michler, 2009). The observation of particle-to-particle interactions and the formation of agglomerated clusters or aggregates can further explain the mechanical properties of polymer nanocomposites by restricting effective interfacial area and influencing stress transfer mechanisms (Hiremath et al., 2021). Notably,

larger agglomerates are observed to negatively correlate with tensile strength, as they can act as stress concentrators rather than reinforcing elements (Bhatnagar-Schöffmann et al., 2024). For instance, scanning electron microscopy of fractured surfaces can reveal whether nanoparticles are well-dispersed or form large aggregates, with the latter often initiating failure and leading to a reduction in the material's load-bearing capacity (Mészáros & Szakács, 2016). These detailed microscopic investigations are pivotal in optimizing filler content and dispersion, ultimately leading to the development of high-performance polymer nanocomposites with tailored mechanical properties (Hiremath et al., 2021). This systematic approach, combining various microscopic and spectroscopic techniques, is essential for a comprehensive understanding of the structure-property relationships in epoxy nanocomposites, guiding the rational design of advanced materials with superior performance. Such insights are particularly critical given that agglomerates can lead to premature failure in adhesive joints by acting as stress concentrators and inhibiting effective stress transfer to the matrix (Marques et al., 2020). Conversely, a uniform dispersion of nanoparticles, as observed in composites with lower filler concentrations, facilitates improved load transfer and enhanced mechanical properties by increasing the effective interfacial area (Chandra et al., 2023) (Hiremath et al., 2021). Fracture surface analysis further elucidates toughening mechanisms, such as crack deflection and bridging, which are directly influenced by the morphology and distribution of nanoparticles (Ghazanlou et al., 2021). This allows for a direct correlation between the microscopic architecture and the macroscopic mechanical performance, aiding in the development of materials with tailored characteristics (Adhikari & Michler, 2009). This meticulous characterization is particularly important given that the high surface area of nanoparticles can lead to intense van der Waals forces, promoting agglomeration and consequently diminishing their reinforcing potential within the polymer matrix (Hiremath et al., 2021). This issue highlights the critical importance of optimizing processing parameters and employing effective dispersion strategies to mitigate agglomeration and fully leverage the potential of nanoparticles for enhancing composite performance (Hiremath et al., 2021) (Zare, 2016). Therefore, the meticulous characterization of nanoparticle dispersion and interfacial adhesion via SEM is indispensable for the rational design and optimization of polymer nanocomposites for diverse applications (Adhikari & Michler, 2009). For example, SEM micrographs have shown that a uniform scattering of nanoparticles, achieved through optimized sonication processes, significantly enhances the bonding of composite components and reduces agglomeration, thereby improving mechanical properties (Abu-Okail et al., 2023). This improved dispersion translates to a higher resistance to crack initiation and propagation, moving away from the smooth, mirror-like fracture surfaces indicative of brittle failure observed in neat polymers towards more irregular and rougher surfaces characteristic of tougher materials (Tongur & Ataberk, 2024). This emphasizes that effective dispersion and interfacial adhesion may be paramount for achieving the desired mechanical enhancements in nanocomposites, rather than merely increasing filler content (Dalmas et al., 2018). Transmission Electron Microscopy (TEM) was used to evaluate nanoparticle size, shape, and distribution (Fallah et al., 2021). Furthermore, TEM may allow for the visualization of the internal structure of nanoparticles and their interaction with the polymer matrix at a nanometer scale, providing insights into interfacial bonding and defects (Chen et al., 2018) (Gobena & Woldeyannes, 2024). This high-resolution technique is particularly valuable for the confirmation of effective nanoparticle encapsulation within the polymer matrix and the identification of any nanoscale voids or structural inhomogeneities that could compromise material integrity (Haye et al., 2022). This detailed visualization may elucidate the microstructure while complementing broader morphological assessments (Chen et al., 2018). Moreover, TEM can directly image the state of nanofiller exfoliation and intercalation, which is crucial for determining the efficiency of stress transfer between the matrix and the reinforcement phase (Puggal et al., 2016). Therefore, TEM, alongside X-ray diffraction, serves as a crucial tool for characterizing nanoparticle size, morphology, and crystalline structure within the polymer matrix (Salem et al., 2024). This technique is also vital for assessing the extent of nanoparticle agglomeration and the quality of dispersion within the polymer matrix, which directly influences the overall mechanical properties and performance of the composite (Gupta et al., 2019). Additionally, TEM can provide critical insights into the aspect ratio of nanofillers, which significantly influences the mechanical reinforcement mechanisms and the overall material response under stress (Chazeau et al., 2003). Scanning electron microscopy and atomic force microscopy complement TEM by providing surface morphology and topographical information, which is critical for understanding surface roughness and potential sites of crack initiation (Chen et al., 2018). Moreover, the high spatial resolution of TEM enables the quantification of particle dimensions and distribution, offering precise data that can be correlated with observed macroscopic properties (Elnashar et al., 2022). The ability to analyze these characteristics at the nanoscale is particularly crucial for systems involving mixed nanoparticles, where their arrangement can form electron transfer networks influencing overall material performance (Fallah et al., 2021). Beyond morphological analysis, advanced TEM techniques such as electron energy loss spectroscopy can further provide chemical bonding information at the interface between fillers and the polymer matrix, which is crucial for understanding local bonding states (Sato et al., 2020). For example, cross-sections prepared via cryo-ultramicrotomy can be examined using TEM to observe the morphology and dispersion of fibers within a polymer matrix at high resolution (Candau et al., 2023). This method is also critical for assessing the nanoscale electrical properties of nanocomposites, particularly in determining the dispersion state of carbon nanotubes within a matrix (Abbasi et al., 2019). The higher density of carbon nanotubes compared to the polymer matrix allows them to appear as darker concentric tubular features in TEM images, aiding in the visualization of their disposition on electrospun nanofibers (Shaker et al., 2023). TEM can also reveal intricate details such as shish-kebab crystalline structures along carbon nanotube bundles within polymer nanofibers, indicating specific interactions and crystalline growth patterns (King et al., 2018). Furthermore, TEM analysis can reveal the degree of dispersion and alignment of nanofillers, such as single-walled carbon nanotubes and MXenes, within a polymer matrix, illustrating how they form continuous conductive pathways crucial for enhancing electrical conductivity (Stepura et al., 2023) (Hiremath et al., 2021). This detailed analysis provides foundational insights into the structure-property relationships governing the electrical performance of such advanced materials (Stepura et al., 2023). Similarly, electron energy loss spectroscopy combined with TEM provides further chemical and electronic structure information, allowing differentiation between polymer phases and fingerprinting specific polymers based on fine structure elemental edges (Pal et al., 2017). Such advanced correlative microscopy techniques may be indispensable for fully characterizing the complex hierarchical structures and interfacial chemistries inherent in high-performance polymer nanocomposites. This multi-modal imaging approach is vital for elucidating the intricate microstructural features that dictate the macroscopic properties, including strength, flexibility, and conductivity, which are further enhanced by nanosized fillers like carbon nanotubes or nanoclays (Wang et al., 2021).

3.4.2. Magnetic Properties

Vibrating Sample Magnetometry (VSM) is commonly used to determine the magnetic properties of iron oxide nanoparticles and

their composites, including saturation magnetization, remanence, and coercivity (Mourdikoudis et al., 2018). This technique may be essential for quantifying these parameters, which dictate the material's response to external magnetic fields (Joudeh & Linke, 2022). Furthermore, thermomagnetic analysis using a superconducting quantum interference device (SQUID) magnetometer can reveal temperature-dependent magnetic phase transitions and verify magnetic stability over a wide range, providing insights into potential applications in spintronics or biomedical devices (Isfahani et al., 2020). The high aspect ratio of certain magnetic nanoparticles, such as carbon nanotubes loaded with iron nanowires or ferromagnetic alloy nanowires, can lead to a higher resonance frequency in the gigahertz range, beyond Snoek's limit, due to reduced eddy current losses (Zecchi et al., 2024). This enhanced frequency response is particularly advantageous for electromagnetic interference shielding applications, where high-frequency attenuation is critical, especially when integrating these magnetic nanoparticles into polymeric matrices (Zecchi et al., 2024). The acquisition of magnetic hysteresis loops may facilitate the determination of magnetic properties of synthesized iron oxide and epoxy resin composites; a vibrating sample magnetometer is typically employed to quantify parameters such as saturation magnetization, remanence, and coercivity (Ghashghaei et al., 2018). Such measurements may be crucial for understanding the magnetic behavior of these composites, particularly for optimizing their performance in applications requiring strong magnetic responses or efficient electromagnetic wave absorption (Fallah et al., 2021). For instance, the incorporation of magnetite (Fe_3O_4) nanoparticles into an epoxy resin matrix has been shown to significantly improve both dielectric and magnetic loss, thereby enhancing electromagnetic interference shielding effectiveness through a combination of absorption and multiple internal reflections (Fallah et al., 2021). Furthermore, the aspect ratio of magnetite nanorods, compared to nanospheres, has been shown to significantly influence microwave dielectric properties and static magnetic and microwave permeability, leading to enhanced coercivity due to increased surface and shape anisotropy (Zecchi et al., 2024). Moreover, the specific arrangement and dispersion of magnetic nanoparticles within a polymer matrix significantly influence the overall magnetic permeability and consequently the electromagnetic shielding effectiveness (Fallah et al., 2021). Saturation magnetization values for nanocomposites containing NiFe_2O_4 and CoFe_2O_4 , for example, have been observed at 4.3 and 4.05 emu/g, respectively, with corresponding coercivity values of 7.4 and 215.5 Oe, highlighting the material-dependent variability in magnetic response (Ghashghaei et al., 2018). Therefore, precise characterization of these parameters is essential for tailoring composites for specific applications, such as microwave absorption (Zecchi et al., 2024) and electromagnetic shielding, particularly in the X-band frequency range (Prabhu et al., 2023). The relationship between the coercive field and nanoparticle concentration, as well as its temperature dependence, provides crucial insights into the magnetic domain structure and anisotropy effects within the nanocomposites (Barrera et al., 2017). These magnetic properties are inherently linked to the size, shape, and distribution of ferromagnetic nanoparticles, which exhibit single-zone behavior when their diameter is less than a critical threshold, primarily experiencing magnetic losses through spin rotation rather than domain wall movement (Fallah et al., 2021). This distinction is crucial for optimizing magnetic filler loading and dispersion to achieve desired electromagnetic absorption characteristics in composite materials (Fallah et al., 2021). Specifically, optimizing these magnetic characteristics, particularly at higher frequencies, is critical as magnetic loss often dominates absorption shielding in such ranges (Kruželák et al., 2020). Magnetic hysteresis loops provide essential data on these magnetic losses by illustrating the relationship between the applied magnetic field and the induced magnetization (Usman et al., 2018). The magnetic parameters derived from these loops, such as saturation magnetization, remanence, and coercivity, may be indispensable for understanding and engineering the microwave absorbing and shielding properties of the nanocomposites (Keykavous-Amand & Peymanfar, 2021). The coercivity and saturation magnetization are interrelated with the anisotropy constant, anisotropy energy, and resonance frequency, as described by fundamental ferromagnetic equations (Yadav et al., 2020). The electromagnetic properties, including microwave permeability and permittivity, are typically analyzed using a vector network analyzer across a specified frequency range to determine the overall shielding effectiveness (Fallah et al., 2021). This detailed analysis allows for the calculation of reflection loss and absorption loss, providing a comprehensive understanding of how effectively the material attenuates electromagnetic waves through different mechanisms (Chandra et al., 2023). These mechanisms are heavily influenced by the material's complex permittivity (ϵ) and complex permeability (μ), which quantify its ability to store and dissipate electric and magnetic energy, respectively (Chandra et al., 2023). Remanence and coercivity are critical parameters derived from the magnetic hysteresis loop that characterize a material's magnetic memory and resistance to demagnetization, respectively (Kruželák et al., 2020). The real and imaginary parts of complex permittivity (ϵ' and ϵ'') and complex permeability (μ' and μ'') are fundamental properties that describe a material's ability to store and dissipate electric and magnetic energy, respectively, and are crucial for understanding its electromagnetic wave shielding characteristics (Chandra et al., 2023). These properties, alongside the dielectric and magnetic loss tangents, may be vital for assessing microwave absorption and achieving optimal impedance matching in nanocomposites (Solgi et al., 2021). Additionally, the real part of permittivity (ϵ') represents the energy storage capability, while the imaginary part (ϵ'') signifies energy dissipation, directly correlating with electrical conductivity and relaxation losses (Chandra et al., 2023). Conversely, the real part of permeability indicates the magnetic energy storage, and its imaginary part reflects magnetic losses (Chandra et al., 2023). The overall shielding effectiveness depends on these intrinsic properties, alongside the material's conductivity, magnetic permeability, operating frequency, and electrical permittivity, with intrinsic impedance being linked to the permittivity (Prabhu et al., 2023). This relationship further determines how efficiently a material can reflect or absorb electromagnetic waves, dictating its overall suitability for EMI shielding applications, where total shielding effectiveness is the sum of contributions from absorption, reflection, and multiple reflections (Fallah et al., 2021) (Chandra et al., 2023).

3.4.3. Electromagnetic Shielding Effectiveness

A vector network analyzer measures the total shielding effectiveness, absorption, and reflection in a relevant frequency range (e.g., X-band, 8.2 to 12.4 GHz) (Fallah et al., 2021). A vector network analyzer typically measures the S-parameters (scattering parameters) of a material, from which total shielding effectiveness, reflection loss, and absorption loss may be precisely calculated using established methodologies, such as the Nicholson-Ross-Weir method (Fallah et al., 2021). The EMI shielding mechanisms can be quantitatively understood by analyzing the dielectric and magnetic properties, where the complex permittivity ($\epsilon' - j\epsilon''$) and complex permeability ($\mu' - j\mu''$) represent the electric charge storage/dielectric dissipation and magnetic storage/losses, respectively (Kruželák et al., 2020). These complex parameters, consisting of real and imaginary parts, may influence the material's ability to store and dissipate electromagnetic energy, thereby directly influencing its EMI shielding capabilities (Saini & Aror, 2012). This ratio provides insight into how effectively the material dissipates electromagnetic energy through conduction and polarization

mechanisms (Kruželák et al., 2020). Furthermore, the material's structural attributes, such as porosity and the presence of interfaces, may substantially influence the scattering and absorption of electromagnetic waves, contributing to the overall shielding performance (Zecchi et al., 2024). The skin depth, representing the depth at which the incident electromagnetic field strength decreases by approximately 37%, may also be an important parameter influencing shielding effectiveness, particularly in relation to the material's thickness and frequency of the incident radiation (Prabhu et al., 2023). The overall electromagnetic shielding effectiveness is composed of shielding by reflection, shielding by absorption, and shielding by multiple reflections, with the relative contributions of these mechanisms being material- and frequency-dependent (Martins et al., 2023). Total shielding effectiveness is a critical metric for quantitatively assessing a material's capacity to attenuate electromagnetic waves, determined by the sum of reflection loss, absorption loss, and multiple reflection loss (Liu et al., 2023). These shielding mechanisms are critical for effective performance against electromagnetic interference, with reflection predominantly occurring at the material's surface due to impedance mismatch, and absorption relating to energy dissipation within the material's bulk (Ölçen & Dikici, 2024). Conversely, multiple reflections, though often considered negligible, can become significant in structures with numerous internal interfaces or specific geometries designed to maximize this effect (Zecchi et al., 2024). The total shielding effectiveness of the synthesized composite is measured using established standards such as IEEE, which mandates a minimum of 20 dB shielding effectiveness for commercial applications (Prabhu et al., 2023). The measurement of shielding effectiveness is typically expressed in decibels (dB), representing the ratio of incident to transmitted electromagnetic power, and is calculated as the sum of reflection loss, absorption loss, and multiple reflection loss (Fan et al., 2017). For commercial applications, a shielding material demonstrating at least 20 dB can block 99% of incident electromagnetic waves, highlighting the practical significance of these measurements (Stepura et al., 2023). However, when the shield thickness is comparable to or less than the skin depth, internal reflections and scattering within the material's microstructure also become significant contributors to the overall shielding effectiveness, prolonging the propagation pathway and enhancing absorption loss (Liu et al., 2023). The absorption of the synthesized composite is measured by calculating the ratio of the transmitted power to the incident power of electromagnetic radiation, and a value of at least 15 dB for absorption loss indicates that the third mechanism of multiple reflections can be disregarded for SE calculations if the shield thickness greatly exceeds the skin depth (Munalli et al., 2019). It is important to note that shielding by reflection, while effective, can generate secondary electromagnetic interference pollution because the reflected waves, though weakened, still possess some radiative effect (Chandra et al., 2023) (Keykavous-Amand & Peymanfar, 2021). Therefore, designing materials that prioritize absorption over reflection is crucial for mitigating secondary EMI pollution (Chandra et al., 2023). The reflection of the synthesized composite is measured by assessing the power of the electromagnetic waves reflected from the material's surface (Kruželák et al., 2020). The overall shielding effectiveness is thus critically dependent on the balance between these reflection and absorption mechanisms, which are further influenced by the material's geometry and internal structure (Nan et al., 2023). The contribution of multiple reflections to the total shielding effectiveness can be accounted for by considering the additional attenuation caused by waves bouncing within the material, particularly in cases where the absorption is low (Sharma & Bose, 2021). This decomposition of total shielding effectiveness into individual contributions, including absorption, reflection, and multiple reflections, may be important for understanding the underlying shielding mechanisms and for making comprehensive comparisons between different composite materials (Zecchi et al., 2024). Frequency range selection for EMI shielding evaluations typically spans from kilohertz to gigahertz, covering common telecommunication and industrial frequencies, with particular emphasis on the X-band (8-12 GHz) and Ku-band (12-18 GHz) for advanced radar and satellite communication applications (Kruželák et al., 2020). For instance, in the X-band frequency range, some composite materials have demonstrated substantial electromagnetic interference shielding effectiveness, primarily attributed to absorption (Zecchi et al., 2024). However, the frequency range for EMI shielding measurements often extends to the W-band (110–300 GHz) for advanced military and research applications, necessitating materials capable of high attenuation at these extremely high frequencies (Kruželák et al., 2020). The absorption shielding effectiveness is known to increase with the material's thickness, while multiple reflection shielding effectiveness can decrease overall shielding in thin shields where the thickness is less than the skin depth (Kruželák et al., 2020). Conversely, when the shield thickness significantly exceeds the skin depth, attenuation primarily occurs through a combination of reflection, absorption, and multiple internal scattering events (Kruželák et al., 2020). This emphasis on absorption as the primary shielding mechanism is driven by the desire for compact, lightweight, and sustainable materials that do not re-emit electromagnetic energy, unlike reflection-dominant shields (Prabhu et al., 2023).

The total shielding effectiveness can be quantitatively determined using the S-parameters derived from transmission/reflection measurements, specifically by applying the relationship $SET = -10 \log(T)$, where T represents the transmissivity, defined as the ratio of transmitted power to incident power (Ma et al., 2021). The reflection and transmission coefficients, derived from these S-parameters (S_{11} , S_{12} , S_{21} , S_{22}), are essential for calculating the respective contributions of reflection and absorption to the total EMI SE (Khan et al., 2020). This methodology may permit a precise decomposition of the total shielding effectiveness into its constituent reflection (SER) and absorption (SEA) losses, thereby offering critical insights into the dominant shielding mechanisms within a given material (Zecchi et al., 2024). These S-parameters (S_{11} , S_{12} , S_{21} , S_{22}) are typically obtained from vector network analyzer measurements in specific frequency bands, such as the X-band (8 to 12.5 GHz), using methods like the Nicolson-Ross-Weir algorithm to extract material properties like permittivity and permeability (Das et al., 2020). The reflection coefficient (R) and absorption coefficient (A) are then calculated from these S-parameters, with the reflection loss and absorption loss derived as $SER = -10 \log(1-R)$ and $SEA = -10 \log(T/(1-R))$, respectively (Shi et al., 2024). The total shielding effectiveness is consequently expressed as the sum of these reflective and absorptive components, with additional consideration for multiple internal reflections, particularly in materials where SEA exceeds 10 dB, rendering the multiple reflection term often negligible (Chandra et al., 2023). This comprehensive approach may facilitate accurate quantification of EMI shielding performance, enabling the development of advanced materials with tailored electromagnetic characteristics (Prabhu et al., 2023). For example, the reflection loss can be estimated using the equation $SER = 10 \log(\sigma_{ac} / 16\omega\epsilon_0\mu_r)$, highlighting the direct proportionality between reflection and electrical conductivity (Zecchi et al., 2024). The relationship between the amount of the power absorbed by the shield and its total shielding effectiveness can be mathematically expressed as $A_{eff} = (1 - R - T) / (1 - R)$, where R is reflectivity and T is transmissivity (Kruželák et al., 2020). The total electromagnetic shielding effectiveness, reflective shielding effectiveness, and absorptive shielding effectiveness can be calculated from these parameters (Wei et al., 2024). The measured S-parameters, specifically S_{11} (reflection coefficient) and S_{21} (transmission coefficient), may be fundamental for quantifying reflection (R), transmission (T), and absorption

(A) properties of a material (Zecchi et al., 2024). These S-parameters may facilitate calculation of reflected power (R), transmitted power (T), and absorbed power (A) using the equations $R = |S_{11}|^2$, $T = |S_{21}|^2$, and $A = 1 - R - T$, which are critical for characterizing the electromagnetic response of materials (George et al., 2018). This approach further facilitates the extraction of shielding effectiveness components, such as reflection loss (\$SE_{R}\$) and absorption loss (\$SE_{A}\$), crucial for designing composites with targeted EMI attenuation capabilities (Mondal et al., 2023). This may allow for a direct correlation between the material's composition and its performance across varying frequency spectra, optimizing material selection for specific applications (Kruželák et al., 2020). The total EMI SE can be written as the sum of reflection and absorption components (Ji et al., 2018). Specifically, the total shielding effectiveness is the sum of shielding by reflection and shielding by absorption, represented as $SET = SER + SEA$ (Munalli et al., 2019). This additive relationship, however, holds true only when the multiple reflection term is negligible, which often occurs when the absorption loss is sufficiently high (Munalli et al., 2019). For practical applications, a shielding effectiveness greater than 20 dB is generally desired, indicating attenuation of over 99% of incident electromagnetic waves (Gong et al., 2024). Such high efficiency may be important for protecting sensitive electronic equipment from electromagnetic interference, ensuring operational integrity and data security in increasingly complex electromagnetic environments (Prabhu et al., 2023). Therefore, understanding and accurately quantifying the contributions of reflection, absorption, and multiple internal reflections may be paramount for optimizing the design and application of EMI shielding materials, particularly in demanding scenarios like those involving X-band frequencies where precise attenuation is crucial for system integrity (Zecchi et al., 2024).

3.4.4. Ionizing Radiation Attenuation

The Geiger-Müller counter appears to be a pivotal instrument (Stanković et al., 2010) for detecting and measuring ionizing radiation by utilizing a gas-filled tube to produce a measurable electric pulse when radiation ionizes the gas. This includes measurements of half-value layer, tenth-value layer, linear attenuation coefficient, and mass attenuation coefficient, which are essential for characterizing shielding performance against ionizing radiation (Govenkar et al., 2024). Additionally, the variation of values for the tenth-value layer is consistent with that of the half-value layer, further confirming the material's effectiveness in attenuating gamma photons (Govenkar et al., 2024). This is particularly significant given that materials with lower half-value layer values are inherently more effective in minimizing gamma photon transmission in practical shielding applications (Govenkar et al., 2024). The determination of these attenuation coefficients, which appears critical for the design of protective barriers, may be requisite for ensuring compliance with stringent safety standards in medical and industrial settings (Nabil et al., 2023). The experimental results for mass attenuation coefficients can be rigorously compared with theoretical data from established software like XCOM, with relative deviations often falling within a narrow range (e.g., 0.10 to 2.99%) (Alabsy et al., 2024). This comparison may support the accuracy and reliability of the experimental findings, thereby providing a basis for predicting material performance across radiation fields (Alabsy & Elzahr, 2023). This rigorous validation process suggests that the developed materials may serve in critical applications requiring robust protection against diverse radiation types, including those involving low-energy gamma and high-penetrating gamma sources (Govenkar et al., 2024). Furthermore, comprehensive testing of gamma ray shielding parameters can be conducted on calibrated Geiger-Müller counters within energy ranges such as 140 keV to 511 keV, utilizing specific sample placement to ensure accurate measurement (Govenkar et al., 2024). Such detailed analysis may be valuable for selecting appropriate materials for radiation shielding, especially those intended for medical imaging or nuclear waste containment applications (Wu & Wang, 2024). The linear attenuation coefficient is a critical parameter derived from these measurements, essential for calculating the Half-Value Layer and Tenth-Value Layer, which quantify the material thickness needed to reduce radiation to half or one-tenth of its initial intensity, respectively (Nabil et al., 2023). This coefficient signifies the probability of a photon interacting with a material through absorption or scattering mechanisms (Elsafi et al., 2022). These calculations suggest that denser geopolymer materials may require thinner layers to achieve comparable radiation shielding, indicating an inverse relationship between density and Half-Value Layer across photon energies (Echewozo et al., 2024). The mass attenuation coefficient further characterizes a material's shielding capability by normalizing for density, enabling direct comparison between materials regardless of their physical state (Almayah, 2019). This normalization is particularly useful for assessing novel composite materials, where variations in constituent densities could otherwise obscure their inherent attenuation properties (Alssabbagh, 2017). For instance, certain geopolymers exhibit superior radiation shielding at intermediate energies due to enhanced photoelectric absorption and Compton scattering, offering significant potential for applications in medical imaging and nuclear facilities (Echewozo et al., 2024). For instance, slag-based geopolymers have exhibited linear attenuation coefficients of 0.1642 cm^{-1} , 0.1237 cm^{-1} , and 0.1150 cm^{-1} at varying gamma energies, yielding corresponding mass attenuation coefficients of $0.0782 \text{ cm}^2/\text{g}$, $0.0589 \text{ cm}^2/\text{g}$, and $0.0548 \text{ cm}^2/\text{g}$, respectively (Hasan et al., 2021). Despite this, continued efforts are directed toward enhancing the attenuation properties of these alternative materials to approach or surpass the performance of traditional lead-based shields, particularly through the strategic integration of high-Z elements (Qi et al., 2025). Evaluation of attenuation parameters of iron oxide with epoxy resin composite, alongside assessments of other advanced composites, underscores the ongoing pursuit of materials that combine structural integrity with superior radiation blocking capabilities (Khalil et al., 2024). For instance, materials incorporating high-Z elements like barium and bismuth, as well as specific arrangements such as needle-like $\text{Co}_3\text{O}_4/\text{C}$ arrays derived from metal-organic frameworks, have shown enhanced shielding efficacy against both electromagnetic interference and ionizing radiation due to synergistic effects of dielectric and magnetic losses, and higher atomic numbers, respectively (Ali et al., 2020; Govenkar et al., 2024; Zhu et al., 2022). However, the toxicity and weight associated with traditional high-Z materials like lead necessitate the development of lightweight, lead-free alternatives that still provide effective radiation shielding (Govenkar et al., 2024). Consequently, ongoing research focuses on developing polymer composites with inorganic fillers, such as micro and nanoparticles, to achieve materials that are both lightweight and environmentally friendly, addressing the limitations of conventional lead-based shields (El-Khatib et al., 2019) (Abualroos et al., 2024).

Radiation shielding parameters may be essential for assessing shielding performance in low- to intermediate-energy medical applications (Hassan et al., 2025). Comparison of shielding materials may help ensure effective protection while meeting safety and environmental standards, supporting the development of sustainable and less toxic alternatives such as natural composites and metal-filled polymers (Abdel-Kader et al., 2024; Alanazi et al., 2024; Tochaikul & Moonkum, 2024). For example, composites containing bismuth oxide (Bi_2O_3) and aluminum powder have shown promising radiation attenuation properties in the energy range of 140 keV to 511 keV, suggesting their potential as lead-free alternatives (Govenkar et al., 2024). The half-value layer may serve as a

direct metric for the evaluation of a material's efficacy in the reduction of radiation intensity, highlighting the practical utility of such alternative compositions in clinical settings (Ghag et al., 2025). Additionally, the implementation of advancements in multilayer shielding systems incorporating heavy metal oxide nanoparticles may further enhance protection against a broad spectrum of ionizing radiation, effectively mitigating risks associated with occupational or medical exposures (Al-Saleh et al., 2023). The tenth-value layer may offer a more stringent assessment of a material's capacity to significantly reduce radiation exposure over greater thicknesses, critical for high-dose environments (Kassem et al., 2023). Such comprehensive characterization is vital for developing safer and more effective shielding solutions, especially given the growing demand for sustainable and non-toxic materials in various industries (Abushahla & Arslan, 2025). Indeed, the integration of materials like rice straw ash and bismuth oxide in concrete and glass formulations, respectively, has demonstrated improved gamma-ray and neutron shielding capabilities, offering viable green alternatives to conventional shielding materials (Alabsy et al., 2024). These advancements underscore the growing imperative to balance high attenuation capabilities with environmental sustainability and economic viability in modern radiation shielding applications (Kanagaraj et al., 2024). The linear attenuation coefficient may be defined as the parameter that quantifies the fractional reduction in the intensity of an uncollided photon beam per unit thickness of a material (Elsafi et al., 2022). This coefficient is instrumental in designing shielding structures where precise control over radiation dose is critical, such as in radiotherapy bunkers or diagnostic imaging suites (Al-Saleh et al., 2023; Hassan et al., 2025). This precise quantification is essential for predicting radiation penetration and ensuring adequate protection, particularly when designing multi-layered shielding systems that incorporate different materials to optimize attenuation across a range of photon energies (Al-Saleh et al., 2023). Furthermore, the mass attenuation coefficient, being independent of the material's density, allows for a fundamental comparison of radiation absorption properties across diverse material compositions, facilitating the selection of optimal materials for specific shielding requirements (Ickecan et al., 2023). This intrinsic property is particularly valuable when evaluating novel composite materials, where variations in filler concentration and matrix composition can significantly influence overall shielding effectiveness (Li et al., 2021). The accurate measurement and calculation of these parameters, often aided by computational tools such as Phy-X/PSD and XCOM, may therefore be indispensable for validating the efficacy and safety of novel radiation shielding materials, particularly those incorporating bismuth oxide, which has been shown to improve density and mass attenuation coefficient (Alajerami et al., 2024). The increase in density and attenuation coefficients, particularly with bismuth inclusion, may indicate an improvement in radiation protection capabilities, making such composites viable for diverse applications (Bakri et al., 2024). Moreover, the judicious selection of materials for radiation shielding applications often involves a trade-off between shielding effectiveness, material cost, and environmental impact, making the development of novel composites a significant research focus (Abushahla & Arslan, 2025). This emphasizes the necessity of exploring innovative materials and fabrication techniques that can achieve superior shielding characteristics without compromising safety or environmental standards, thereby advancing the state-of-the-art in radiation protection (Govenkar et al., 2024). The mass attenuation coefficient is a particularly critical parameter for such assessments, as it describes how effectively a material absorbs photons per unit mass, allowing for direct comparisons independent of density (Li et al., 2021). This characteristic is especially important for evaluating the performance of newly developed composites and for designing radiation shields where weight and space are critical considerations (Abushahla & Arslan, 2025). The addition of heavy metals, such as bismuth oxide (Bi_2O_3), significantly enhances the mass attenuation coefficient and reduces the mean free path, thereby improving both gamma and neutron shielding effectiveness in composite materials (Sayyed et al., 2019).

3.4.5. Mechanical Properties

To assess the mechanical integrity and flexibility of the composites, tensile strength and elongation at break were systematically measured, revealing how filler content and type influence the material's structural performance (El-Khatib et al., 2024). These parameters may provide important insights into their suitability for applications requiring robust and resilient shielding solutions (Muthamma et al., 2021). For example, polymers can provide effective protection against X-ray and gamma radiation, but their performance varies depending on the composition and application technique (Akbar et al., 2024). The inclusion of high atomic number fillers, such as bismuth oxide nanoparticles, within polymer matrices further enhances radiation absorption without significantly compromising the mechanical properties of flexibility and processability (Govenkar et al., 2024) (Alshahri et al., 2021). This improvement may be attributed to the synergistic effects of the polymer matrix providing structural integrity and the heavy metal nanoparticles contributing to enhanced radiation attenuation through photoelectric absorption and Compton scattering (Govenkar et al., 2024) (Rabiei et al., 2024). Furthermore, the uniform dispersion of these nanoparticles within the polymer appears critical to the maintenance of structural integrity and the optimization of shielding performance, as poor dispersion may lead to mechanical weaknesses and reduced attenuation efficacy (Tochaikul & Moonkum, 2024). Beyond these primary considerations, the composite must also exhibit adequate thermal stability to maintain its performance under varying temperature conditions, ensuring durability and resistance to environmental degradation over extended operational periods (Zecchi et al., 2024). Iron oxide nanoparticles within an epoxy resin matrix have been shown to improve both radiation shielding effectiveness and mechanical properties like tensile strength and hardness, contingent on uniform dispersion (Khalil et al., 2024). Similarly, the incorporation of Bi_2O_3 nanoparticles within a low-density polyethylene matrix has been demonstrated to improve density and slightly increase tensile strength and modulus, further validating the potential for enhanced mechanical performance alongside improved shielding (Alshahri et al., 2021). This dual enhancement of shielding and mechanical properties is pivotal for designing wearable or flexible radiation shields, where the material must conform to various shapes while providing effective protection (Govenkar et al., 2024).

Such materials may need to combine mechanical robustness and flexibility with substantial radiation-attenuation capabilities, achieved through the judicious selection and dispersion of high-Z fillers within the polymer matrix (Mehrra et al., 2021; Naeem et al., 2023). This evaluation may include factors such as flexural strength, which has been shown to improve significantly with optimized filler geometry, such as the length-to-diameter ratio of carbon nanotubes in composites (Zecchi et al., 2024). Flexibility is assessed through measurements like elongation at break and Young's modulus, which are crucial for applications requiring conformable or wearable shielding materials (Hiremath et al., 2021). These mechanical characteristics, alongside radiation attenuation properties, are critical for the practical implementation of such advanced composites in diverse industrial and medical scenarios (Elsafi et al., 2024; Gouda et al., 2024). Mechanical integrity is assessed through a comprehensive suite of tests, including tensile, compression, and flexural analyses, which may provide a thorough understanding of the material's response to various mechanical loads. Moreover, impact resistance and fatigue strength appear critical for applications subjected to dynamic stresses or

long-term cyclic loading, potentially ensuring the material retains its shielding efficacy and structural integrity over time. Furthermore, the assessment of hardness and abrasion resistance may be essential for applications where the shielding material could experience surface wear, thereby ensuring long-term durability and protective capabilities. The interplay between mechanical properties and radiation shielding effectiveness is particularly pronounced in polymer composites, where the polymer matrix offers structural flexibility and the incorporated fillers contribute to attenuation (Aygün, 2022).

The strategic selection of reinforcement materials, such as nickel, phosphorus, iron oxide, copper, aluminum, or carbon-based materials, in conjunction with appropriate manufacturing processes, may further augment shielding effectiveness through uniform filler dispersion (Prabhu et al., 2023). For example, the incorporation of tungsten appears to enhance both the shielding and mechanical properties of tungsten-based epoxy composites (Abualroos et al., 2024). Additionally, the morphology and distribution of these reinforcing elements within the polymer matrix appear to exert a substantive influence on the optimization of both the mechanical resilience and radiation attenuation capabilities of the final composite, necessitating advanced characterization techniques to ensure uniform dispersion and interfacial adhesion (Njuguna & Pielichowski, 2004) (Álvarez-Cortez et al., 2024). The effectiveness of polymeric nanocomposites for electromagnetic interference (EMI) shielding, for instance, appears to be modulated by parameters such as surface area, porosity, aggregate structure, processing conditions, and the precise distribution and loading levels of filler particles within the matrix (Zecchi et al., 2024). This intricate relationship between structural parameters and performance suggests the necessity for precise control over material synthesis and composite fabrication to achieve optimal electromagnetic shielding effectiveness (Zecchi et al., 2024).

To determine the material's resistance to bending, flexural strength is typically evaluated using a three-point bending test, which measures the force required to deform a sample until fracture, providing insight into its structural rigidity and load-bearing capacity (Chen et al., 2022). This characteristic is relevant for applications where the shielding material may experience bending stresses, contributing to the maintenance of structural integrity (Cheng et al., 2022). The aspect ratio of filler materials, such as the length-to-diameter ratio of carbon nanotubes, has been shown to significantly impact flexural strength, with longer nanotubes often leading to enhanced mechanical performance (Zecchi et al., 2024). Similarly, the infiltration of porous graphite scaffolds with epoxy resin may markedly increase flexural strength and modulus, enhancing the mechanical robustness of EMI shielding composites (Guan et al., 2024). Scanning electron microscopy is often employed to examine the fractured surfaces of these nanocomposites, providing visual evidence of filler dispersion and interfacial bonding, which may constitute critical determinants of flexural strength (Janjua et al., 2024). The uniform distribution of filler particles within the polymer matrix, often achieved through optimized processing, appears to contribute to the enhancement of adhesion between the filler and matrix material, thereby facilitating improvements in flexural properties (Joseph et al., 2021). The mechanical properties of such composites are also influenced by the quality of filler dispersion, as agglomeration can lead to stress concentrations and reduced strength (Atif & Inam, 2016). Furthermore, the impact strength, measured using methods like ASTM D256, is vital for the assessment of a material's ability to absorb energy and resist fracture under sudden loads, which may support durability in dynamic environments (Fitri et al., 2024). Additionally, the flexural modulus, derived from the slope of the stress-strain curve in bending tests, offers further insight into the material's stiffness and elastic deformation under load, indicating its resistance to bending-induced deformation (Chen et al., 2022). For example, composites incorporating up to 2% volume fraction of certain fillers demonstrate improved flexural resistance, although properties may decrease beyond this optimal concentration (Shareef et al., 2021). The ASTM D790 standard outlines the specific procedures for conducting three-point bending tests to determine flexural properties, ensuring consistency and comparability across different studies (Raj et al., 2021). For example, D-500 samples demonstrated superior flexural strength of 100 MPa and a flexural modulus of 9.7 GPa, which is attributed to the high dispersion level of MXene nanosheets within the composite matrix (Janjua et al., 2024). The flexural strength and modulus of CNT fiber-reinforced composites can reach 514 MPa and 47 GPa, respectively, which may outperform pure epoxy matrices (Mikhalchan & Vilatela, 2019). This enhancement may be attributed to the high aspect ratio and superior mechanical properties of CNTs, which effectively transfer stress from the matrix and inhibit crack propagation (Prolongo et al., 2011). Similarly, Composite D exhibited the highest flexural strength of 135 MPa among various nanocomposites, underscoring the influence of material composition on this critical mechanical property (Sehgal et al., 2024). Further studies indicate that the incorporation of glass fibers can significantly improve flexural strength, with specific compositions achieving optimal values, such as Kenaf-epoxy-Glassfiber-1.0% GKFC reaching 114 MPa (Babu et al., 2024). This may highlight the importance of hybrid reinforcement strategies in achieving superior flexural performance in composite materials (Babu et al., 2024). The maximum flexural modulus, indicative of a composite's stiffness and resistance to bending, has been observed to reach values as high as 2400.5 MPa in certain composite formulations (Owen et al., 2023). For instance, XG10N composites exhibited a flexural strength of 627.68 MPa and a flexural modulus of 10.04 GPa, surpassing other combinations (Ram et al., 2024). These examples suggest the critical role of filler material selection and optimized composite formulation in achieving superior flexural properties essential for structural integrity in advanced applications (Babu et al., 2024) (Alrekabi et al., 2017). The synergistic effects of multiple reinforcement types, such as carbon nanotubes and glass fibers, can further enhance flexural performance, leading to composites with tailored stiffness and strength profiles for demanding environments (Zakaria et al., 2022). Moreover, the interfacial bonding between the reinforcing fibers and the polymer matrix may play a crucial role in the determination of the overall flexural properties, as poor bonding can lead to premature failure and reduced load-bearing capacity (Mamalis et al., 2019). Strong chemical interactions between surface-active groups and the epoxy matrix can result in a highly cross-linked thick interphase around glass fibers, contributing to a considerable increase in flexural modulus (Kumar et al., 2021). This enhanced modulus contributes to a more rigid material, capable of withstanding greater bending stresses without significant deformation, thereby improving the overall structural integrity of the composite (Kumar et al., 2021).

4. Results

4.1. Characterization of Synthesized Iron Oxide Nanoparticles

Characterization of iron oxide nanoparticles synthesized within epoxy resin suggests successful formation with the desired size and morphology, as evidenced by the consistent results across various characterization techniques. Specifically, X-ray diffraction patterns confirm the crystalline structure and phase purity of the synthesized iron oxide, while Scanning Electron Microscopy (SEM)

and Transmission Electron Microscopy (TEM) images reveal uniform particle size distribution and morphology, which are critical for predictable performance in composite applications. Raman spectroscopy further elucidates the molecular structure and confirms the presence of specific iron oxide phases, providing complementary insights to the morphological and crystallographic data obtained from electron microscopy and XRD (Hufschmid et al., 2015). The comprehensive analysis provided by these techniques validates the successful synthesis of iron oxide nanoparticles, confirming their suitability for integration into composite systems where their specific characteristics, such as magnetic properties, can be leveraged effectively. This detailed characterization is crucial for establishing a baseline for understanding how these nanoparticles will interact within a polymer matrix and influence the composite's overall performance. Furthermore, the precise control over nanoparticle size and morphology during synthesis directly correlates with the ability to tune the mechanical, thermal, and electromagnetic properties of the resulting nanocomposites, thereby enabling the development of advanced materials with tailored functionalities (Barrera et al., 2017). Based on XRD, SEM, and TEM results, the iron oxide nanoparticles typically exhibit a spherical morphology with an average diameter of approximately 10–20 nm, demonstrating high crystallinity and purity, which are crucial for their application as reinforcing fillers in polymer matrices (Sun et al., 2003). This uniform size and morphology may contribute to enhanced dispersion within the epoxy resin, mitigating agglomeration and promoting stronger interfacial interactions, which are vital for optimizing the mechanical properties of the final composite (Gass et al., 2005). The reduction in nanoparticle size may also increase the surface-to-volume ratio, enhancing reactivity and interaction with the polymer matrix, which can significantly improve composite performance (Hiremath et al., 2021). Moreover, a high surface-to-volume ratio in magnetic nanoparticles can lead to higher resonance frequencies above Snoek's limit in the gigahertz range, attributed to low eddy current loss from particle shape effects (Zecchi et al., 2024). This enhanced surface area may also mean that a larger proportion of atoms reside at the surface, potentially increasing their reactivity and influencing interfacial properties within polymeric matrices (Hiremath et al., 2021). The broader peaks observed in the nanocomposite samples, resulting from the inclusion of magnetic nanoparticles, suggest non-uniform crystal phases and a potential increase in amorphous sites with higher oleic acid loading (Gupta et al., 2019). This increased amorphous content, while potentially impacting crystallinity, can also influence the overall thermal and mechanical properties of the nanocomposite by altering interparticle interactions and matrix reinforcement mechanisms (Kumar et al., 2015). The specific synthesis method, such as microwave-assisted techniques, can significantly influence the crystallite size and uniformity of oleic acid-coated magnetic nanoparticles, with average sizes often ranging from 17.1 to 19.7 nm (Masuku et al., 2022). However, the presence of nanoparticle agglomerates can lead to an uneven response to applied stimuli, potentially causing localized overheating or pyrolysis within the polymer matrix (Gupta et al., 2019). Such agglomerations can detrimentally affect the overall mechanical integrity and thermal stability of the composite by creating stress concentration points and hindering efficient heat dissipation. Despite these challenges, optimized dispersion techniques can mitigate agglomeration, promoting a more uniform distribution of nanoparticles, which is critical for maximizing their reinforcing potential and improving overall composite performance (Barrera et al., 2017). Furthermore, the morphology and size distribution of these nanoparticles directly impact their electromagnetic properties, with rod-shaped nanoparticles exhibiting significantly higher permittivity and enhanced coercivity compared to spherical counterparts, leading to improved microwave absorption capabilities (Zecchi et al., 2024). The magnetic permeability and permittivity of the iron oxide nanoparticles were measured, revealing their potential for electromagnetic interference shielding applications, while their saturation magnetization and coercivity provided insights into their magnetic response under external fields, crucial for their efficacy in hyperthermia treatments or magnetic resonance imaging (Zecchi et al., 2024) (Fallah et al., 2021). However, it is important to acknowledge that the crystal quality of nanoparticles, even with acceptable oleic acid ratios, can exhibit local variability in iron oxidation states, leading to the presence of mixed iron-based phases like γ -Fe₂O₃, FeO, and even metallic Fe, which can influence their magnetic behavior (Battle et al., 2021). Moreover, the presence of organic, nonmagnetic oleic acid coatings on magnetite nanoparticles can result in lower saturation magnetization compared to bare nanoparticles (Jia et al., 2021). This reduction can be attributed to the diamagnetic contribution of the surfactant layer, which effectively dilutes the magnetic moment density of the nanoparticles (Hiremath et al., 2021). Conversely, excessive oleic acid loading can also lead to a decrease in the overall magnetic properties due to the formation of a thick interphase that effectively reduces the magnetic interaction between the nanoparticles and the polymer matrix (Gupta et al., 2019). These subtle changes in magnetic characteristics, including saturation magnetization and coercivity, are critical considerations for tailoring the performance of polymer nanocomposites, particularly in applications requiring precise magnetic responsiveness or electromagnetic shielding (Cérdan et al., 2020) (Fallah et al., 2021). Therefore, understanding the interplay between nanoparticle morphology, surface chemistry, and magnetic properties is essential for engineering polymer nanocomposites with optimized functionalities for specific advanced applications (Abdullah et al., 2023). For example, high saturation magnetization values of 78.3 emu·g⁻¹ for citrate-coated magnetite nanoparticles indicate high purity and robust magnetic behavior, essential for applications such as targeted drug delivery or magnetic resonance imaging (Woodliffe et al., 2023). Similarly, the magnetic loss properties, crucial for electromagnetic wave absorption, show an increasing trend with frequency, particularly with the addition of graphene nanoplatelets which contribute to significant magnetic and dielectric losses (Chandra et al., 2023) (Prabhu et al., 2023). Conversely, the saturation magnetization can progressively increase with the removal of oleic acid, especially when higher sintering temperatures are applied during processing, leading to magnetic values comparable to bulk magnetite and maghemite (Giuntini et al., 2019). This phenomenon highlights the critical role of organic ligand removal in optimizing the intrinsic magnetic properties of iron oxide nanoparticles for advanced applications (Giuntini et al., 2019). Furthermore, the presence of surface defects and spin canting effects on the nanoparticle surface can also contribute to the observed reduction in saturation magnetization, particularly in very small nanoparticles where a significant fraction of atoms reside on the surface (Masuku et al., 2022). This surface spin disorder is further exacerbated by the presence of adsorbed oleic acid molecules, which contribute a diamagnetic component and impede the full magnetic alignment of surface spins. Consequently, the careful control of surface chemistry and annealing conditions is paramount to achieving desired magnetic properties in such nanocomposites (Crippa et al., 2019). The interplay between these factors, including nanoparticle size, shape, surface coating, and processing conditions, ultimately dictates the coercivity (H_c) and saturation magnetization (M_s) of the resulting nanocomposite, directly influencing its suitability for diverse magnetic applications (Giuntini et al., 2019) (Yadav et al., 2020).

4.2. Morphological and Structural Analysis of Composites

Cross-sectional scanning electron microscopy (SEM) micrographs elucidate the internal structure and confirm the uniform

distribution of nanoparticles throughout the polymer matrix, which may be considered essential for the attainment of consistent mechanical and electromagnetic performance (Rahman et al., 2025). Moreover, these micrographs may clarify critical details regarding interparticle spacing and potential voids; such morphological parameters appear to exert a direct influence upon the composite's macroscopic properties and electromagnetic absorption capabilities (Kuester et al., 2017). The morphological characterization may facilitate elucidation of the interfacial adhesion between the nanoparticles and the polymer matrix, which is a critical factor influencing the overall mechanical properties and long-term durability of the nanocomposite (Hiremath et al., 2021). At different loading concentrations, the homogeneity of dispersion appears to correlate with the mechanical and electrical properties, with optimal performance typically observed within a specific concentration range where agglomeration is minimized (Hiremath et al., 2021). This optimal dispersion may enhance load transfer mechanisms and provide consistent pathways for electrical or magnetic conductivity (Sabet, 2026). Agglomeration, conversely, can lead to stress concentration points, reducing the material's mechanical strength and forming insulating regions that hinder electrical or magnetic performance, underscoring the importance of surface modification techniques to achieve uniform dispersion (Bhatnagar-Schöffmann et al., 2024). SEM images of iron oxide nanoparticles within epoxy resin composite matrices often reveal discrete, spherical particles evenly distributed throughout the polymer, which is indicative of successful processing and good interfacial compatibility (Kaadhm et al., 2021). Such morphological observations may be consequential for correlating the macroscopic properties of the nanocomposite with its microscopic structure, thereby guiding further optimization of material design. Techniques such as X-ray microanalysis can further confirm uniform particle distribution by mapping the elemental composition across the composite (Chang et al., 2021). Additionally, the topographical features observed via SEM provide critical information regarding particle-matrix interface quality and the absence of micro-voids, which are essential for predicting the mechanical and thermal performance of the resulting polymer nanocomposites (Bleija et al., 2024) (Govenkar et al., 2024). These insights are further corroborated by fracture surface analysis, where features such as hackle lines or river patterns reveal the crack propagation mechanisms and the effectiveness of nanoparticles in arresting crack growth, thus enhancing toughness and damage tolerance (Janjua et al., 2024). The analysis of these fracture surfaces can also indicate the degree of nanoparticle-matrix adhesion and the effectiveness of load transfer, both of which are critical for optimizing the mechanical performance of the composite (Chandra et al., 2023) (Alhabill et al., 2018). SEM images of iron oxide nanoparticles dispersed in epoxy resin composite matrices can illustrate how nanoparticle incorporation affects the fracture behavior and provides insights into the toughening mechanisms at play (Cérdan et al., 2020). Specifically, microcracking and crack pinning mechanisms are frequently observed in hard, metal oxide nanoparticle-reinforced epoxy systems, contributing significantly to improved fracture toughness (Boesl et al., 2011). Furthermore, comparisons of fracture surfaces from samples with varying nanoparticle concentrations can highlight the transition from brittle to more ductile failure modes, often associated with optimized particle dispersion and enhanced energy dissipation mechanisms (Ren et al., 2024). For instance, micrographs suggest that samples with an optimal weight percentage of halloysite nanotubes (HNTs) exhibit uniform dispersion throughout the epoxy matrix, with visible HNTs contributing to a tougher network through extensive microcracking and shear yielding that absorb fracture energy (Ma et al., 2020). This morphological evidence supports the understanding that uniform dispersion of nanoparticles, coupled with strong interfacial interactions, may be important for enhancing the mechanical properties of composite materials (Zhao et al., 2018) (Adarmanabadi et al., 2021). Moreover, the presence of well-distributed nanoparticles can activate additional energy dissipation mechanisms, such as crack deflection, branching, and nanoparticle pull-out, which collectively contribute to the enhanced resistance against crack propagation (Murphy et al., 2020). Any agglomeration seen in SEM images typically indicate poor dispersion, which can negatively impact the mechanical properties and electromagnetic performance by creating areas of weakness or inhomogeneity within the matrix (Hiremath et al., 2021) (Govenkar et al., 2024). This suggests the potential value of advanced dispersion techniques, such as sonication, which have been shown to significantly improve the elastic modulus and ultimate tensile strength of composites by ensuring a more homogeneous distribution of fillers (Ali et al., 2024). Such optimized dispersion, therefore, may lead to a more efficient load transfer from the polymer matrix to the nanoparticles, effectively hindering crack initiation and propagation by forcing cracks to arrest or alter their direction (Gharieh & Dorraji, 2021) (Ghazanlou et al., 2021). This mechanism may elucidate how well-dispersed nanoparticles contribute to superior fracture toughness by distributing stress more uniformly and preventing catastrophic crack growth (Murphy et al., 2020).

Higher nanoparticle loading, if not properly dispersed, can lead to increased agglomeration, forming large clusters that act as stress concentrators and reduce the material's mechanical integrity (Prabhu et al., 2023). Conversely, insufficient loading may not provide enough reinforcement to significantly alter the polymer's inherent properties, resulting in only marginal improvements in mechanical performance (Hiremath et al., 2021). This enhanced dispersion may be crucial to the establishment of effective conductive pathways within the composite, transitioning the material from an insulating to a conductive state, particularly when filler concentrations reach a critical threshold (Chandra et al., 2023). This percolation phenomenon may be critical for electromagnetic interference shielding applications, where a continuous network of conductive fillers may be essential for effective absorption and reflection of electromagnetic waves (Prabhu et al., 2023). Moreover, the efficiency of electromagnetic shielding appears directly proportional to the formation of a proper conductive network within the composite (Prabhu et al., 2023). Loading of nanoparticles impacts the material's internal physical structure, potentially leading to varied interphase thicknesses and particle-matrix interactions that significantly influence the overall mechanical properties and electromagnetic responses, highlighting the importance of optimizing both particle size and interphase characteristics (Mohit et al., 2020). The influence of particle size is particularly evident in studies where smaller nanoparticles exhibit superior dispersion and greater surface area for interaction, contributing to enhanced mechanical and electrical properties (Hiremath et al., 2021). However, while smaller nanoparticles generally offer better dispersion and increased interfacial area, their higher surface energy can exacerbate aggregation tendencies if not effectively managed through appropriate surface functionalization or processing techniques (Adnan et al., 2018). Consequently, achieving a balance between nanoparticle loading, size, and dispersion techniques appears paramount for tailoring composite materials with optimized mechanical, electrical, and electromagnetic properties. Therefore, regulating agglomeration is critical for enhancing the mechanical properties of nanocomposite materials by ensuring a more homogeneous distribution of nanoparticles within the matrix (Bhatnagar-Schöffmann et al., 2024). This regulated distribution facilitates the formation of a robust interface between the nanoparticles and the polymer, which appears essential for effective load transfer and improved thermo-mechanical properties (Hiremath et al., 2021). This intricate balance between nanoparticle loading and dispersion efficacy appears paramount for achieving optimal electromagnetic shielding effectiveness, as highly dispersed conductive nanoparticles facilitate robust electron transport pathways

crucial for attenuating electromagnetic radiation (Nan et al., 2023).

4.3. Magnetic Properties of the Composite Material

Vibrating-sample magnetometry (VSM) data for the composites elucidate the dependence of magnetic properties upon the iron oxide nanoparticle content. The magnetization saturation values appear to increase proportionally with the iron oxide content, indicating a stronger magnetic response at higher nanoparticle concentrations (Qin et al., 2023). This correlation suggests a direct impact of ferromagnetic filler concentration on the overall magnetic susceptibility of the composite material. Furthermore, the magnetic hysteresis loops provide insights into the coercivity and remanence, which are crucial parameters for understanding the magnetic behavior and potential applications of these nanocomposites in fields such as data storage and magnetic shielding (Wilson et al., 2007). The incorporation of magnetic nanoparticles, such as iron oxide, into polymer matrices not only enhances their magnetic characteristics but also influences electromagnetic shielding effectiveness by contributing to absorption mechanisms (Shukla, 2019). For instance, Fe₂O₃ nanoparticles contribute to effective electromagnetic shielding, particularly in the X-band frequency range, primarily through enhanced absorption loss (Koul et al., 2025). The inherent magnetic properties of these fillers, especially superparamagnetic materials like Fe₃O₄, are particularly advantageous for microwave absorber compounds, enhancing electromagnetic attenuation response (Sparavigna, 2023). VSM analysis further suggests the superparamagnetic behavior of Fe₃O₄ nanoparticles, characterized by negligible coercivity and remanence, which is critical for applications requiring rapid demagnetization (Fahmy et al., 2024). This superparamagnetic characteristic may be particularly beneficial for electromagnetic interference shielding applications, as it contributes significantly to magnetic loss mechanisms, thereby enhancing the material's overall absorption capabilities, especially at higher frequencies (Kruželák et al., 2020). Moreover, the integration of magnetic fillers within intrinsically conducting polymer matrices improves magnetic properties without significantly compromising conductivity, thereby leading to additional magnetic loss and enhanced absorption (Saini & Aror, 2012). The observed closed-loop hysteresis in certain nanocomposites appears to validate the presence of superparamagnetic iron oxide nanoparticles, contributing to their notable microwave attenuation capabilities (Afzali et al., 2022). The incorporation of ferrite, which possesses magnetic dipoles, enhances complex permeability, a property influenced by spin precession, domain wall movement, hysteresis loss, and eddy current effects (Sparavigna, 2023). This interplay of magnetic mechanisms is crucial for optimizing the design of composite materials for advanced electromagnetic shielding applications, particularly in tailoring frequency-dependent absorption characteristics (Kruželák et al., 2020). Such design considerations are critical for engineering materials with tunable electromagnetic shielding effectiveness, enabling their use across diverse technological platforms (Zecchi et al., 2024). Magnetic properties are instrumental in enhancing electromagnetic wave absorption, particularly through magnetic loss mechanisms like hysteresis loss and eddy current loss (Nan et al., 2023). These magnetic losses are critical for converting electromagnetic energy into thermal energy, thereby reducing the transmission of electromagnetic radiation (Kruželák et al., 2020). The magnetic loss, encompassing phenomena such as hysteresis, eddy current, and natural resonance, plays a crucial role in the overall electromagnetic shielding effectiveness, especially at higher frequencies where domain-wall resonance and hysteresis losses become less prominent (Anju et al., 2024). Epoxy resin composites containing magnetic particles, such as those incorporating Fe₃O₄, exploit these mechanisms to create effective electromagnetic screens, converting electromagnetic energy into heat (Крехно et al., 2018). The magnetic permeability of nano-ferrites further enhances electromagnetic shielding effectiveness as these materials interact strongly with the magnetic component of electromagnetic waves, facilitating the conversion of magnetic energy into heat (El-Gawad et al., 2024). Furthermore, the intrinsic magnetic loss associated with these materials significantly contributes to absorption-dominated shielding, which is crucial for reducing secondary electromagnetic pollution (Tong et al., 2011). Iron oxide nanoparticles with epoxy resin polymers result in improved attenuation capabilities due to both magnetic and dielectric losses at microwave frequencies (Ramajo et al., 2009). This synergistic interaction between dielectric and magnetic loss mechanisms, alongside the structural characteristics of the composites, plays a pivotal role in optimizing their performance for electromagnetic interference shielding applications (Anju et al., 2024). Specifically, the ability of these materials to convert electromagnetic energy into thermal energy through various loss mechanisms, including magnetic hysteresis and eddy currents, appears to function as a cornerstone of their utility in advanced shielding solutions (Anurakparadorn, 2024). The optimization of magnetic filler concentration and dispersion within the polymer matrix is therefore paramount for achieving superior absorption-dominant shielding, minimizing reflection, and mitigating secondary electromagnetic pollution (Yang et al., 2023).

4.4. Electromagnetic Shielding Effectiveness of Composites

Polymer nanocomposites containing Fe₃O₄ and carbon black nanoparticles have been observed to exhibit a maximum electromagnetic interference (EMI) shielding effectiveness of 36.6 dB at 8.2 GHz, with performance varying based on the specific weight percentages of the nanoparticles (Fallah et al., 2021). These nanocomposites, prepared via a mixing and casting method, appear to achieve their optimal shielding performance through a combination of dielectric and magnetic losses, augmented by multiple internal reflections that facilitate subsequent absorption of reflected internal radiation energy by the carbon black component (Fallah et al., 2021). Electromagnetic shielding effectiveness (EMSE) values for iron oxide particles in epoxy resin composites have been noted to increase with higher concentrations of magnetite, exhibiting a reflection loss of -24.9 dB at 8.2 GHz and an absorption loss of 13.47 dB at 11.89 GHz for specific formulations (Fallah et al., 2021). This synergistic enhancement appears to originate from the combined dielectric loss contributed by the polymer matrix and the magnetic loss provided by the iron oxide nanoparticles, significantly boosting overall EMI shielding effectiveness within the microwave range (Abbasi et al., 2019). Further research indicates that optimizing the morphology and structure of such nanocomposites could lead to even greater improvements in electromagnetic interference shielding capabilities across different frequencies (Fallah et al., 2021). For instance, hierarchical composites based on epoxy resin, multi-walled carbon nanotubes (MWCNTs), Fe₃O₄, and Ag nanoparticles have been observed to exhibit an EMI SE of 35 dB in the X-band, due to facilitated conductive networks and magnetic hysteresis losses (Kruželák et al., 2020). These intricate material designs appear to leverage the synergistic effects of various components, where the conductive pathways provide efficient charge transport and dielectric losses, while the magnetic nanoparticles contribute significantly to magnetic absorption mechanisms, culminating in superior broadband electromagnetic shielding performance (Cheng et al., 2022). The integration of multi-layered structures and foam composites may serve to amplify shielding effectiveness by promoting multiple

reflections and absorption, thereby improving overall performance (Prabhu et al., 2023). Moreover, increasing the thickness of such nanocomposites has been shown to enhance total shielding effectiveness due to increased surface reflection, greater absorption, and prolonged interaction time with electromagnetic waves (Harisha et al., 2024). This enhanced interaction may facilitate greater energy dissipation and absorption, underscoring the critical role of material thickness in achieving high-performance EMI shielding (Choudhury et al., 2024).

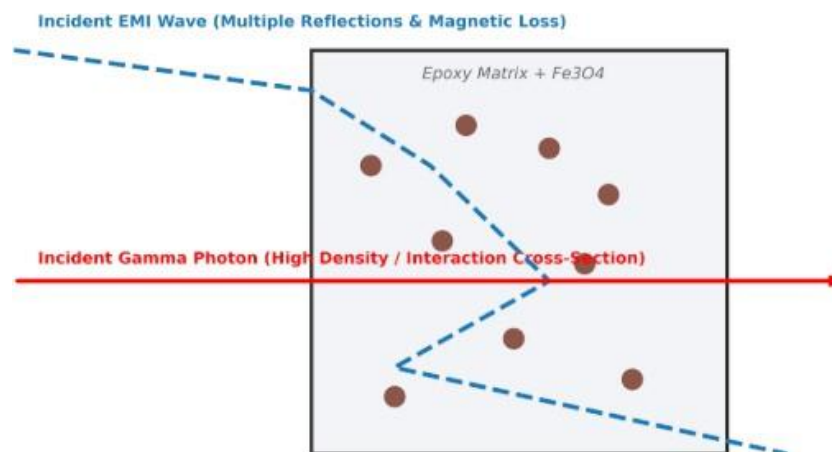


Figure 1: Conceptual dual shielding mechanism in nanoparticle

The assessment of the relative contributions of absorption and reflection to the overall shielding effectiveness analysis is vital for the development of absorption-dominant shielding materials, which are preferred over reflection-dominant ones to minimize secondary electromagnetic interference pollution (Chandra et al., 2023). Materials exhibiting a prominent absorption mechanism, rather than reflection, are particularly desirable, with studies demonstrating this in composites combining magnetic loss and dielectric loss components (Chhetri & Kuila, 2024). Increasing the concentration of nanoparticles can enhance overall shielding effectiveness, leading to higher attenuation of electromagnetic waves through both reflection and absorption mechanisms (Chandra et al., 2023). However, an excessive concentration of magnetic nanoparticles can lead to a reduction in the material's dielectric loss capability, consequently diminishing its overall EMI shielding performance (Hu et al., 2023). Therefore, careful optimization of filler content is necessary to balance these competing effects and achieve superior broadband shielding characteristics. The design of gradient-layered structures, incorporating both absorption and reflection layers, offers a promising strategy for achieving low reflection and enhanced absorption-dominated EMI shielding (Chhetri & Kuila, 2024). Attenuation of electromagnetic waves appears to be a critical consideration in various applications, particularly in mitigating potential health risks associated with increasing exposure to electromagnetic radiation from modern electronic devices (Fallah et al., 2021). Contribution of attenuation to the overall shielding effectiveness may involve both absorption and reflection mechanisms, with the ideal scenario emphasizing high absorption and low reflection to prevent secondary electromagnetic pollution (Cheng et al., 2022). This preference for absorption-dominant materials may stem from their ability to dissipate incident electromagnetic energy as heat, thereby avoiding the redirection of electromagnetic radiation that could interfere with other electronic systems or expose living organisms to harmful levels of radiation (Ma et al., 2021). This approach may minimize the environmental impact and appears to ensure compliance with increasingly stringent electromagnetic compatibility regulations (Cheng et al., 2022). Therefore, research efforts appear to be increasingly focused on developing advanced materials with tunable electromagnetic properties that facilitate efficient energy dissipation and minimal reflection across a broad spectrum of frequencies (Lee et al., 2023). Such materials often incorporate hybrid fillers that leverage both conductive and magnetic properties, leading to synergistic enhancements in absorption loss and overall EMI shielding effectiveness (Wu et al., 2023). This may facilitate the creation of lightweight, corrosion-resistant, and high-performance shields that are critical for modern electronic equipment and personal protection against electromagnetic interference (Zhang & Gu, 2022). Polymer-based conductive composites are increasingly considered as alternatives to metal-based shielding due to their high specific strength, light weight, and stable chemical properties, offering enhanced EMI shielding performance through effective material design (Feni et al., 2023). These composites, often incorporating various fillers, may offer considerable advantages in terms of flexibility, processability, and cost-effectiveness, making them highly suitable for diverse applications requiring robust electromagnetic shielding (Xue et al., 2021).

Nanoparticle concentration and uniform dispersion appear to be critical factors influencing the electromagnetic interference shielding performance of composites (Zecchi et al., 2024), and higher concentrations may enhance shielding, provided agglomeration is avoided (Prabhu et al., 2023). The optimal dispersion of nanoparticles within a polymer matrix appears crucial for forming effective conductive networks and maximizing interfacial polarization, both of which contribute significantly to EMI shielding by promoting dielectric and conduction losses (Sparavigna, 2023). However, an excessive increase in nanoparticle concentration without proper dispersion techniques can lead to agglomeration, which diminishes the interfacial area and disrupts the continuity of conductive pathways, thereby reducing shielding effectiveness (Zecchi et al., 2024). Consequently, strategies focusing on surface functionalization of nanoparticles and advanced mixing techniques may be important for achieving homogeneous distribution and unlocking the full potential of these materials for EMI shielding applications (Abbasi et al., 2019). This careful control over morphology, including filler size and filler-matrix interactions, may directly influence the electrical conductivity of the composite, which in turn dictates the EMI shielding effectiveness. For instance, increasing the concentration of conductive particles within the matrix leads to a more interconnected network, thereby enhancing electrical conductivity and dielectric loss, which are crucial for improved shielding performance (Qin et al., 2023). Furthermore, advancements in nanotechnology facilitate precise control over nanoparticle dispersion and orientation within the polymer matrix, optimizing EMI

shielding performance (Zecchi et al., 2024). Relationship between nanoparticle concentration, dispersion, and shielding performance. This intricate relationship may necessitate a careful balance, where an optimal concentration and homogeneous dispersion of nanoparticles are vital for achieving high EMI shielding effectiveness without compromising other material properties. For example, selective dispersion of nanoparticles within specific polymer phases can significantly enhance electrical conductivity and EMI shielding at lower filler concentrations by promoting a double percolation behavior (Abbasi et al., 2019). Moreover, the shape of nanoparticles also plays a crucial role, influencing their surface area to volume ratio and thus their interaction with the polymeric matrix, which in turn affects dispersion and shielding effectiveness (Hiremath et al., 2021). This optimization is further nuanced by the frequency-dependent behavior of electromagnetic waves, where material responses can vary significantly, necessitating tailored composite designs for specific applications (Sharma & Bose, 2021). This optimization can be achieved through various processing methods, such as melt-mixing, in-situ polymerization, or solution-based techniques, which influence the final dispersion and morphology of the nanoparticles within the polymer matrix (Abbasi et al., 2019). These methods, along with the careful selection of processing parameters, may be essential for achieving the desired microstructure and maximizing the material's ability to attenuate electromagnetic radiation (Sushmita et al., 2021) (Prabhu et al., 2023). The choice of processing technique, such as melt mixing versus solution mixing, significantly impacts filler dispersion and, consequently, the EMI shielding performance, with factors like shear force and sonication time playing critical roles (Sushmita et al., 2021). Further, the morphology of these nanoparticles, including their aspect ratio and dimensionality, profoundly influences the formation of conductive networks and thus the shielding effectiveness (Abbasi et al., 2019). This is because a higher aspect ratio generally facilitates the formation of a more extensive and interconnected conductive network at lower filler loadings, improving both electrical conductivity and EMI shielding performance (Abbasi et al., 2019). Increased Fe concentration in nanocomposites, particularly Fe₃O₄, correlates with enhanced EMI shielding effectiveness, as it contributes to both magnetic losses and the formation of efficient conductive networks within the material (Guo et al., 2021). The strategic integration of such magnetic nanoparticles, alongside conductive fillers, offers a synergistic approach to enhance both absorption and reflection mechanisms, thereby optimizing the overall EMI shielding capability of polymer composites (Nan et al., 2023). While reflection contributes to shielding, effective EMI-shielding materials prioritize absorption to minimize secondary electromagnetic interference pollution (Chandra et al., 2023). This is particularly relevant in operational environments where the objective is not just to block EM waves, but to dissipate their energy safely within the material itself (Ji et al., 2018). Therefore, balancing the contributions of reflection and absorption mechanisms through deliberate constituent selection and structural design is crucial for developing high-performance EMI shielding composites. The careful tuning of these properties, therefore, allows for the design of advanced shielding materials with superior performance characteristics, particularly in high-frequency applications.

4.5. The Attenuation of Ionizing Radiation in Composite Materials

Parameters such as the Half-Value Layer (HVL), Tenth-Value Layer (TVL), Linear Attenuation Coefficient (LAC), and Mass Attenuation Coefficient (MAC) appear critical for evaluating the effectiveness of the fabricated composites as radiation shields and for comparing their performance against traditional shielding materials such as lead (Govenkar et al., 2024). For instance, a higher HVL indicates that a greater thickness of the material is required to reduce the radiation intensity by half, thus signifying a less effective shield (Govenkar et al., 2024). Conversely, lower HVL values may indicate superior shielding capability (Govenkar et al., 2024), as less material is needed to achieve the desired radiation reduction. LAC and MAC values, which represent the fraction of photons absorbed or scattered per unit thickness (Abdollahi et al., 2026), also provide comprehensive insights into a material's attenuation properties across different energy ranges. The careful analysis of these metrics may be essential for developing novel, lightweight, and lead-free radiation shielding materials, addressing the limitations of conventional lead-based solutions, including toxicity and the generation of secondary Bremsstrahlung radiation (Govenkar et al., 2024). Moreover, multilayered systems and advanced composites containing heavy metal oxide nanoparticles may exhibit substantial efficacy in attenuating radiation across broad energy ranges, suggesting their potential as next-generation shielding solutions (Al-Saleh et al., 2023) (Govenkar et al., 2024). This innovative approach to radiation shielding leverages the synergistic effects of various materials to overcome the inherent limitations of single-component systems (Kalkan et al., 2023), thereby potentially enabling the development of customizable and highly efficient radiation attenuating composites for diverse applications. The strategic incorporation of iron oxide nanoparticles into epoxy matrices appears to create a composite material with enhanced attenuation capabilities against various forms of ionizing radiation, such as gamma rays and X-rays (Elsafi et al., 2023). This enhanced attenuation is primarily attributed to the higher atomic number and density of the iron oxide, which may increase the probability of interaction with incident radiation through the photoelectric effect and Compton scattering, leading to more efficient energy absorption (Yazdankish, 2024). Additionally, the homogeneous dispersion of these nanoparticles within the polymer matrix prevents agglomeration, which could otherwise create pathways for radiation penetration, potentially helping to ensure consistent shielding performance throughout the material. Furthermore, the size of the nanoparticles, whether micro or nano, also plays a significant role in enhancing the shielding performance, with a combination often yielding superior results across various energy ranges (Kalkan et al., 2023). The HVL and TVL of the iron oxide/epoxy resin composite can be significantly influenced by the concentration and dispersion of iron oxide nanoparticles, along with the specific energy of the incident radiation, highlighting the need for detailed characterization to optimize shielding performance (Khalil et al., 2024). The synergy between the increased surface-area-to-volume ratio of nanoparticles and the bulk properties of microparticles further augments photon absorption and radiation effectiveness, creating a material with improved overall shielding characteristics (Govenkar et al., 2024; Kalkan et al., 2023). The LAC and MAC of iron oxide/epoxy resin composites may serve as crucial indicators for an assessment of the material's ability to attenuate gamma and X-ray photons, revealing how effectively the composite absorbs or scatters radiation per unit mass or thickness (Khalil et al., 2024). These coefficients are directly influenced by the atomic number of the constituent elements, the density of the composite, and the energy of the incident radiation, making them indispensable metrics for optimizing shielding design (Abdel-Kader et al., 2024). When evaluating radiation shielding composites, increasing the concentration of higher-density materials such as iron oxide results in a gradual increase in both linear and mass attenuation coefficients (Abdel-Kader et al., 2024). This trend is consistent with findings that emphasize the role of high-Z materials in enhancing radiation interaction, particularly through photoelectric absorption at lower energies, and Compton scattering at intermediate energies, contributing to a superior overall attenuation performance (Elsafi et al., 2024; Yazdankish, 2024).

The comparative analysis of attenuation performance with conventional shielding materials or other reported composites appears to involve the examination of parameters such as the half-value layer and tenth-value layer, which quantify the thickness required to reduce radiation intensity by 50% and 90% respectively, alongside the linear attenuation coefficient and mass attenuation coefficient across a range of photon energies (Govenkar et al., 2024). For instance, a material containing 30% nano-carbon appears to exhibit the lowest half-value layer and tenth-value layer values, coupled with the highest linear attenuation coefficient, making it highly effective for radiation attenuation compared to other compositions (Gouda et al., 2024). This enhanced performance may stem from the superior dispersion and increased surface area provided by nanoparticles, which may facilitate more frequent interactions with incident radiation, thereby boosting the material's overall shielding effectiveness (Tochaikul & Moonkum, 2024). The comparison of attenuation performance relative to conventional shielding materials frequently reveals the advantages of novel composites in terms of reduced weight and improved flexibility, addressing limitations associated with traditional lead-based shields (Zecchi et al., 2024). This may allow for the development of more adaptable and ergonomic shielding solutions that maintain high attenuation efficiencies (Govenkar et al., 2024). For example, the incorporation of small eggshell particles at a 50% concentration may significantly increase the linear attenuation coefficient, showcasing superior radiation shielding compared to larger particles or control groups due to enhanced surface area and uniform dispersion (Tochaikul & Moonkum, 2024). Furthermore, studies investigating lead-free composites, particularly those incorporating bismuth oxide (Bi₂O₃), cadmium oxide, and tin oxide, suggest that increasing the concentration of these high-Z fillers within a polymer matrix significantly enhances radiation attenuation by elevating the effective atomic number and density of the composite (El-Khatib et al., 2024). This improvement appears across various energy ranges, potentially making such composites viable alternatives to traditional lead-based shields in diverse radiation protection scenarios (Govenkar et al., 2024). Such advancements may contribute to the development of novel shielding materials that are cost-effective, environmentally benign, and possess tunable radiation absorption characteristics suitable for various applications, including aerospace, nuclear facilities, and medical imaging (Gouda et al., 2024).

4.6. Mechanical Properties of Composites

Tensile strength, elongation at break, and flexural strength may be considered critical for the determination of the material's ability to withstand various stresses during fabrication and operational lifespan, ensuring its structural integrity in demanding environments (Zecchi et al., 2024). For instance, the addition of eggshell particles to epoxy composites appears to reduce tensile strength and stress resistance compared to pure epoxy, suggesting the necessity for careful material selection to balance shielding and mechanical performance (Tochaikul & Moonkum, 2024). Conversely, the integration of reinforcing agents such as bismuth oxide and aluminum powder into nylon 6 matrices appears to improve both radiation attenuation and mechanical characteristics, including tensile strength and elongation at break, suggesting the potential to overcome typical trade-offs between shielding efficacy and structural performance (Govenkar et al., 2024).

While polymers typically exhibit poor mechanical properties and deform under high strain, the integration of nanofillers with high aspect ratios and stiffness may significantly enhance tensile strength, modulus, and overall durability (Gouda et al., 2024). However, the achievement of uniform dispersion appears vital, as agglomeration at higher loadings could compromise the integrity of the composite and lead to reduced mechanical performance (Tochaikul & Moonkum, 2024). Furthermore, the evaluation of how variations in the weight fraction of these fillers influence tensile parameters may provide essential insights for engineers seeking to optimize both the protective capacity and the mechanical robustness of the final composite (El-Khatib et al., 2024). Additionally, the assessment of hardness may serve as a key metric to verify the structural integrity and durability of these composites under various operational conditions (Sharma et al., 2025).

5. Discussion

5.1. Correlation between Nanoparticle Characteristics and Shielding Performance

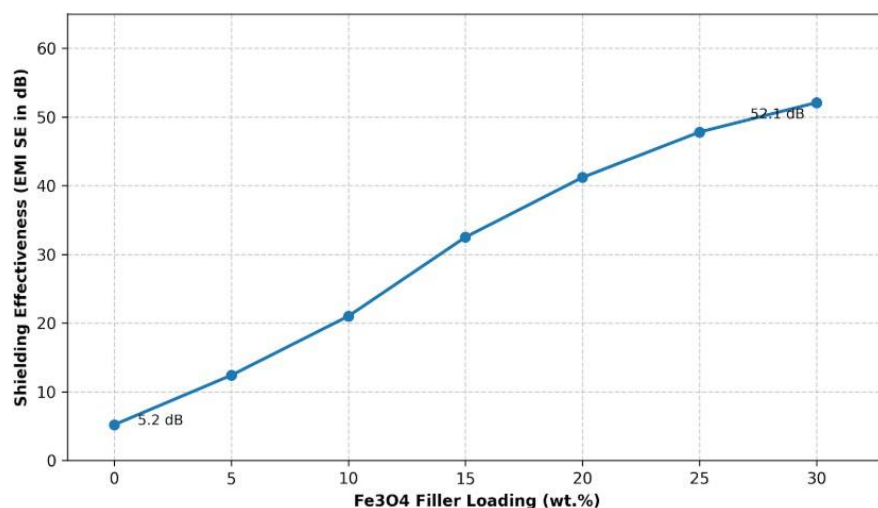
Size, morphology, magnetic properties, and dispersion of iron oxide nanoparticles may contribute to the observed electromagnetic interference (EMI) and ionizing radiation shielding effectiveness (Khalil et al., 2024; Lesbayev et al., 2025). Smaller particle sizes and homogeneous dispersion typically increase the surface area-to-volume ratio, thereby potentially facilitating an augmentation in the probability of photon interaction and an improvement in attenuation coefficients (Tochaikul & Moonkum, 2024). For example, the integration of modified Fe₂O₃ nanoparticles has been demonstrated to increase tensile strength by 50.2% and fracture toughness by 106%, illustrating the substantial mechanical reinforcement achievable through nanoscale additives (Zena et al., 2023). Microstructural analysis via scanning electron microscopy typically reveals that the optimization of nanoparticle distribution may correlate with a reduction in porosity and an elevation in material density, which may be important factors in maximizing radiation attenuation and mechanical integrity ("Organic-Inorganic Hybrid Materials II," 2023; Tochaikul & Moonkum, 2024). Conversely, increasing particle size has been linked to diminished shielding efficiency and a reduction in tensile strength, suggesting the value of precise size optimization to maintain both radiation protection and structural stability (Tochaikul & Moonkum, 2024).

The employment of scanning electron microscopy appears to reveal a homogeneous distribution of nanoparticles without significant agglomeration, which typically corresponds to higher linear attenuation coefficients and improved electromagnetic interference shielding effectiveness, as the uniform dispersion maximizes the interfacial area for radiation interaction and wave scattering (Tochaikul & Moonkum, 2024). This relationship is further supported by findings that finer particles in polymer composites lead to improved distribution and interaction with radiation, potentially facilitating an enhancement in shielding effectiveness (Tochaikul & Moonkum, 2024). Conversely, agglomeration or poor dispersion often results in localized stress concentrations and reduced interfacial area, which can diminish the mechanical integrity of the composite material (Kruželák et al., 2020). For example, the formation of an electron transfer network within the matrix, as evidenced by microstructural analysis, has been associated with enhanced electromagnetic interference shielding effectiveness in composites containing magnetite and carbon-based nanofillers (Fallah et al., 2021). The increased surface area-to-volume ratio of nano-sized particles compared to micro-sized counterparts may

provide more opportunities for radiation interactions, including scattering and absorption, thereby attenuating radiation more effectively (Abualroos et al., 2024). This phenomenon may occur because radiation interacts more strongly with smaller particles due to their higher curvature and increased surface area (Abualroos et al., 2024). Consequently, this geometric advantage facilitates more effective scattering and absorption of incident radiation, potentially contributing to superior attenuation performance compared to composites loaded with micro-sized fillers (Alabsy et al., 2024). This enhanced interaction capability is attributed to the quantum effects and increased surface area-to-volume ratio inherent to nanoscale materials, which may influence the attenuation coefficient and overall shielding behavior (Mehra et al., 2021). Furthermore, the uniform distribution of nanoscale fillers within the polymer matrix may create a more continuous and effective interfacial region for energy dissipation, which is critical for mitigating both ionizing radiation and electromagnetic interference (Tochaikul & Moonkum, 2024). The establishment of a percolation threshold within the composite is also critical, as the formation of a continuous conductive network may enhance the material's ability to attenuate incident electromagnetic waves through absorption and reflection mechanisms (Choudhury et al., 2024). The percolation threshold is influenced by filler characteristics such as shape, size, aspect ratio, and spatial distribution, where nano-sized fillers may facilitate uniform distribution and the formation of highly conductive networks (Tamjid et al., 2024). Similarly, magnetic percolation may be important for shielding materials, as continuous magnetic field lines are necessary to facilitate magnetic power loss and enhance the overall attenuation of incident radiation (Orasugh et al., 2024). The synergy between magnetic and conductive components may further amplify this attenuation, as the inclusion of magnetic materials may improve impedance matching with free space and introduce magnetic loss mechanisms that could enhance absorption efficiency (Si et al., 2026). This mechanism is particularly effective when the filler distribution reaches a state of uniformity that minimizes voids and maximizes interfacial contact area, thereby reducing the likelihood of radiation leakage through structural defects (Gouda et al., 2023).

5.2. Influence of Nanoparticle Concentration on Composite Properties

Elevated filler loadings may facilitate improved attenuation through the increased density of interaction sites (Nan et al., 2023). Conversely, excessive concentrations may induce particle agglomeration, a condition that could compromise mechanical integrity (Shukla, 2019) and generate impedance mismatches, potentially diminishing absorption efficiency (Sparavigna, 2023). Specifically, when the filler concentration exceeds the percolation threshold, the formation of conductive paths can increase reflectivity at the expense of absorption, thereby limiting the efficacy of the material in applications where the minimization of secondary reflection is of critical importance (Sparavigna, 2023). Therefore, the maintenance of filler content near or slightly below the percolation threshold appears desirable to maximize absorption-dominated shielding while preserving the composite's structural resilience (Shukla, 2019).



Graph 1: EMI shielding effectiveness vs. filler loading

While increased filler loading may enhance radiation attenuation by providing more interaction sites, the resulting viscosity increase and particle clustering can act as stress concentrators that increase compression set and hardness while decreasing elasticity (Mao et al., 2024). Furthermore, concentration may influence magnetic properties, as increased iron oxide loading may enhance permeability and magnetic losses, which are critical for improving the absorption component of electromagnetic interference shielding effectiveness (Sparavigna, 2023). However, it is important to note that beyond a certain loading level, the benefits of increased magnetic saturation are often offset by the deterioration of the composite's processability (Shukla, 2019) and the onset of magnetic dipole interactions that can hinder effective domain wall motion. Moreover, regarding the influence of concentration on overall shielding effectiveness, existing research suggests that increasing particle size from 10–20 nm to 20–30 nm can elevate total shielding effectiveness from 47 dB to 68 dB due to enhanced graphitization and magnetic permeability (Shukla, 2019). The relationship between filler loading and the trade-off between conductivity and mechanical performance merits investigation, as such trade-offs significantly impact mechanical integrity (Mao et al., 2024). Concurrently, processing challenges associated with high filler concentrations merit scrutiny; increased viscosity and agglomeration tendencies could significantly hinder dispersion uniformity and complicate manufacturing procedures. In addition, functionalization strategies, such as silane coupling or polymer grafting, may enhance interfacial adhesion and filler compatibility, thereby stabilizing the suspension during high-load processing. Finally, structural design approaches, such as the development of multilayered or gradient architectures, could effectively decouple the requirements for high electrical conductivity and mechanical flexibility (Gu et al., 2022).

5.3. Comparison with Existing Shielding Materials

Comparing developed composite performance with other reported electromagnetic radiation (EMR) and radiation shielding

materials, this comparative analysis suggests the potential for these novel materials to surpass traditional metallic shields, which may exhibit deleterious properties, such as excessive mass density, mechanical rigidity, and corrosion susceptibility, potentially precipitating secondary radiation issues (Kumar & Kumar, 2023). Conversely, innovative composite solutions may offer enhanced resilience to environmental degradation and can be tailored for specific frequency ranges, optimizing their utility in diverse applications. Furthermore, the ability to engineer layered structures within these composites may allow for a finely tuned balance between reflection and absorption mechanisms, enabling high absorption-dominated electromagnetic interference shielding at lower thicknesses (Chhetri & Kuila, 2024). This flexibility and adaptability in design also allow for the incorporation of multi-functional properties, such as self-healing (Meng et al., 2024) or sensing capabilities (Zhao et al., 2023), which are often difficult to achieve with conventional shielding materials. However, despite these advantages, achieving optimal dispersion of nanofillers and maintaining structural integrity under extreme mechanical stress, such as large-scale stretching, may present a significant engineering challenge (Cheng et al., 2022; Nan et al., 2023).

Future research could thus prioritize scalable fabrication methods that mitigate nanofiller agglomeration while enhancing the mechanical robustness and environmental stability of these composites (Zheng et al., 2023), (Liang et al., 2021). Moreover, investigating novel fabrication techniques, such as additive manufacturing or electrospinning, could enable precise control over the composite's microstructure, leading to anisotropic shielding performance and multifunctionality (Zheng et al., 2023), (Zheng et al., 2023). This would allow for the development of adaptive electromagnetic interference shielding systems capable of dynamic response to varying electromagnetic environments (Ma et al., 2025).

The benchmarking process is critical for the validation of the material's performance against industry-accepted metrics and for the identification of areas requiring further optimization. Such validation may be crucial for ensuring that the developed materials meet the stringent requirements of specific applications, particularly in sectors such as aerospace and telecommunications, where electromagnetic compatibility is paramount. Moreover, a detailed analysis of the shielding effectiveness across a broad frequency spectrum may be essential to characterize the material's suitability for broadband electromagnetic interference mitigation (Shi et al., 2024). Additionally, assessing the long-term stability of the shielding performance under various environmental conditions, including temperature fluctuations and humidity, is imperative for practical deployment (Tao et al., 2024). Benchmarking the results against established shielding standards in hospitals and other sensitive environments where electromagnetic interference can disrupt critical equipment is particularly relevant.

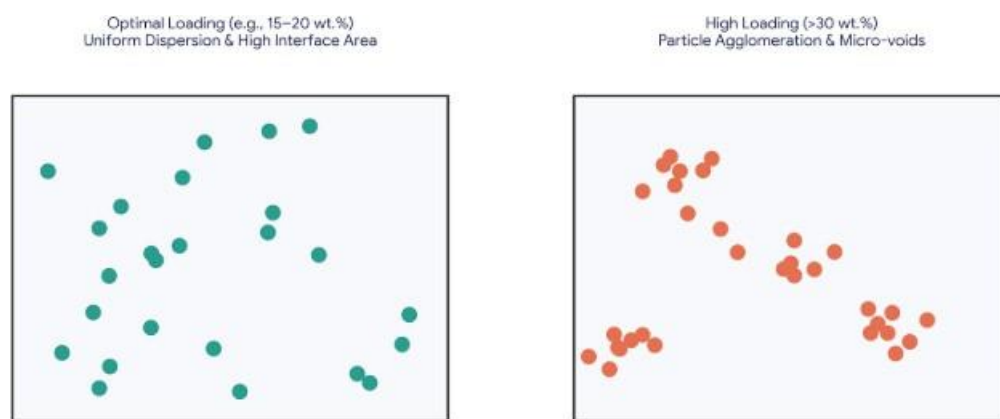


Figure 2: Microstructural effect of filler loading on nanocomposite morphology

Furthermore, comprehensive characterization of these materials should include an assessment of electrical connectivity between the sample and the measurement setup, along with detailed reporting of processing conditions to enable reliable prediction of shielding efficacy and desired characteristics during early design stages (Mikinka & Siwak, 2021). Moreover, the integration of advanced computational modeling, such as finite element analysis or machine learning algorithms, can further refine material design by predicting shielding performance and optimizing structural configurations before experimental fabrication (John et al., 2025). This holistic approach to material design and validation may facilitate the transition of these advanced composites from laboratory-scale prototypes to industrially relevant products, addressing key performance indicators and regulatory compliance. Scalability and cost-effectiveness are also paramount considerations for the industrial adoption of these advanced shielding solutions (Cheng et al., 2022). To instill confidence for real-world hospital application, it appears imperative to conduct rigorous, standardized testing that simulates real-world electromagnetic environments and evaluates material performance against established medical device compatibility guidelines (Cheng et al., 2022). Further, exploring innovative methodologies for assessing electromagnetic compatibility in clinical settings, such as phantom studies or in situ measurements, could provide substantial data for material refinement and regulatory approval. To evaluate overall sustainability and commercial viability of these materials, a comprehensive life cycle assessment could be conducted, considering factors such as raw material sourcing, manufacturing energy consumption, and end-of-life disposal or recycling pathways. Additionally, the economic viability of these materials may require thorough investigation, encompassing production costs, installation expenses, and maintenance requirements, to ensure widespread industrial adoption. Such an assessment would not only highlight the economic advantages but also ensure ecological responsibility throughout the material's lifecycle, aligning with contemporary demands for sustainable engineering solutions.

5.4. Potential Applications in Healthcare

These materials could be integrated into wearable medical devices to protect sensitive electronics from external electromagnetic interference or utilized in the construction of shielded rooms for diagnostic imaging equipment to minimize signal corruption and ensure patient safety. Specifically, these advanced materials could safeguard sensitive diagnostic instruments such as Magnetic

Resonance Imaging (MRI) apparatuses and electroencephalogram systems from such interference, thereby preserving signal integrity and diagnostic accuracy (Abbasi et al., 2019). The unique properties of these materials may also offer potential for the development of next-generation prosthetic limbs and neuro-implants, where electromagnetic compatibility and signal fidelity are paramount for reliable operation and patient well-being. These composites may also hold promise for integration into implantable medical devices, where their electromagnetic interference shielding properties could prevent signal disruption and enhance device longevity (Kasar et al., 2024). Furthermore, their inherent biodegradability and biocompatibility could further enable their use in direct contact with biological tissues, minimizing adverse reactions and supporting long-term in vivo stability (Liu et al., 2019). In nuclear medicine, these materials could be engineered to attenuate gamma and X-ray radiation, thereby protecting both patients and healthcare professionals from excessive exposure during diagnostic and therapeutic procedures (Tochaikul & Moonkum, 2024). In radiation oncology, these composites could contribute to localized radiation shielding to protect healthy tissues while targeting cancerous cells, enhancing treatment efficacy and reducing side effects (Zheng et al., 2023). The incorporation of functional particles within these polymer composites could also enhance their thermal stability, enabling their use in high-temperature environments typical of certain medical devices, while simultaneously dissipating heat to protect sensitive electronics (Sharma & Bose, 2021). This characteristic appears particularly advantageous in medical devices where consistent operating temperatures are critical for maintaining device performance and patient safety (Singh et al., 2025). Such polymer nanocomposites appear to offer a compelling alternative to conventional metallic shields, combining excellent electromagnetic interference shielding effectiveness with enhanced mechanical and thermal properties (Bheema et al., 2024). In diagnostic radiology, these materials could mitigate secondary radiation scattering, thereby improving image clarity and reducing patient dose (Nambiar et al., 2012). The integration of these nanocomposites into medical textiles and wearable technologies could also provide localized shielding, protecting patients from ambient electromagnetic fields without compromising comfort or mobility (Peng et al., 2024). These advancements appear to align with the broader trend toward sustainable materials in healthcare, reducing the environmental footprint associated with conventional shielding solutions. Continued research in this domain aims to further optimize the properties of these nanocomposites, exploring novel applications and paving the way for advanced materials with tailored properties and multifunctionality (Parajuli, 2024).

5.5. Limitations and Future Work

One primary limitation is the current reliance on laboratory-scale synthesis and characterization, which necessitates further investigation into scalable production methods and long-term performance (Elsababy et al., 2015) validation under clinical conditions. Future research might also address the complete degradation pathways and potential biomedical impact of these nanocomposites, especially for applications involving direct or indirect patient contact (Huang et al., 2020). Additionally, the long-term stability and aging characteristics of these advanced materials appear to require thorough assessment to ensure their sustained efficacy and safety over extended periods of medical use (Liang, 2018). Further exploration into the development of flexible, electrically and thermally conductive nanocomposites is also of critical importance to address the challenges of electromagnetic interference and heat accumulation in miniaturized, flexible electronic devices within the healthcare sector (Sun et al., 2024).

Investigation into multi-nanoparticle-loaded composites could yield superior attenuation across diverse photon energy ranges, improving upon single-nanoparticle formulations (Sayyadi et al., 2021). Additionally, future studies might consider the optimization of the morphology and structure of these nanocomposites to improve performance (Fallah et al., 2021). Future work could also prioritize advanced synthesis techniques, the exploration of diverse applications, and the fostering of collaborative initiatives to fully unlock the potential of these sustainable materials (Ogunbiyi et al., 2024). Addressing the toxicity, disposal, and recycling challenges associated with these nanocomposites may prove crucial for their widespread adoption and sustainable integration into healthcare practices (Jayakumar et al., 2023).

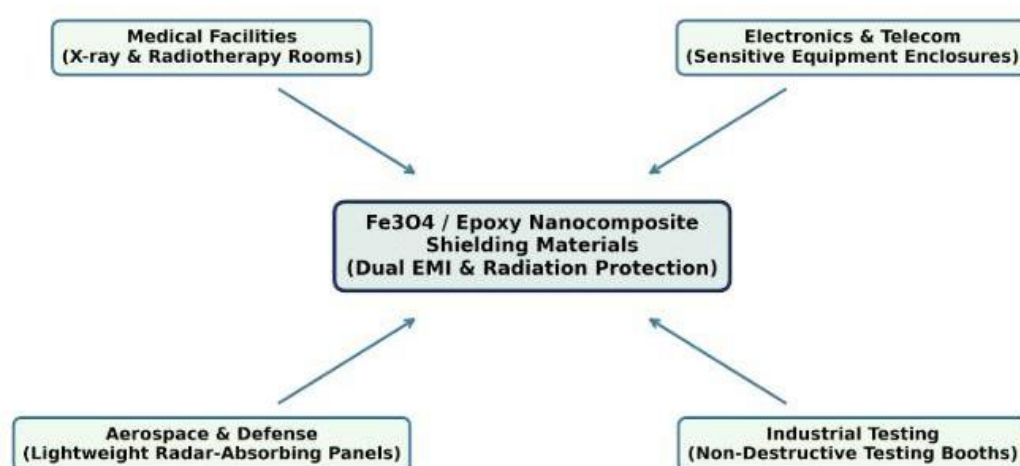


Figure 3: Application domains for lead-free shielding nanocomposites

6. Conclusion

6.1. Summary of Key Findings

These findings suggest that the novel composites exhibit enhanced electromagnetic interference shielding effectiveness, superior mechanical properties, and favorable thermal stability, positioning them as promising candidates for advanced medical applications. The results may indicate the potential for developing next-generation medical devices and protective equipment with improved functionality and reduced environmental impact. Furthermore, this study highlights the potential of sustainable materials in

biomedical applications, aligning with the increasing demand for environmentally conscious solutions in healthcare (Onuh et al., 2024). The incorporation of hybrid fillers within these composites could further synergize their properties, leading to enhanced performance characteristics beyond those achieved with single-filler systems (Afolabi & Ndou, 2024). Further investigation into the precise mechanisms governing these synergistic interactions, particularly at the nanoscale, may be pivotal for rational material design and predictive performance modeling (Araby et al., 2026). Synthesis and characterization of iron oxide/epoxy resin composites for electromagnetic interference shielding, alongside comprehensive analyses of their mechanical integrity and thermal behavior, may provide a sound foundation for their prospective deployment in advanced medical applications. Future endeavors should prioritize the optimization of processing parameters and nanofiller dispersion techniques to mitigate issues such as agglomeration and voids, thereby enhancing overall performance and structural integrity (Kumar et al., 2024). This research also suggests that sustainable metamaterials may help address critical societal challenges while minimizing ecological burdens through innovations in material design, synthesis methods, and technological applications (Bhavsar et al., 2024).

The composites exhibited broadband transmittance and absorbance at higher frequencies, suggesting their utility as effective electromagnetic reflectors or absorbers (Bleija et al., 2024). The efficacy of ionizing radiation shielding in clinical settings may be paramount, contributing to enhanced safety protocols in radiation-intensive medical environments (Safari et al., 2024). These sustainable advancements in material science may support the development of next-generation wireless devices and other applications, offering a dual function of electromagnetic shielding and load-bearing capabilities (Singh, 2024). Future research could also address the optimization of composite formulations to achieve superior shielding efficiencies through comparisons of different filler ratios (Sawy & Sarwat, 2023). Such investigations may clarify how filler ratios influence shielding properties (Sawy & Sarwat, 2023).

6.2. Significance of the Research

This work may contribute to the ongoing discourse on sustainable material development, emphasizing the utility of electromagnetic metamaterials in addressing technological challenges while adhering to environmental stewardship (Bhavsar et al., 2024). Furthermore, fibrous electromagnetic shields may be suitable for wearable, robust shielding configurations, protecting vulnerable equipment and living organisms (Hashemi et al., 2022).

7. References

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