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PERFORMANCE, DESIGN STRATEGIES, AND APPLICATIONS OF COMPOSITE MATERIALS FOR ELECTROMAGNETIC AND MAGNETIC SHIELDING: A LITERATURE REVIEW

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Abstract. *Electronic devices and wireless systems have been on the rise increasing the demand of effective electromagnetic interference (EMI) and magnetic shielding solutions. Despite its effectiveness, traditional metallic shields possess drawbacks in terms of size, rigidity, prone to corrosion and incapable of being fitted with other systems in the modern compact system. Composites made of polymer and carbon have become promising alternatives, with lightweight, flexible and tunable shielding properties. This review discusses the growing demand for shielding and the shortcomings of traditional materials, followed by the fundamental principles of EMI and magnetic shielding. Standardized characterization and measurement techniques are then discussed, with an overview of conventional metallic shields. Also, it determines the structural designs, fabrication techniques, and performances of polymer- and carbon-based composite materials across low- and high-frequency regimes. The practical uses of composites in aerospace, electronics, wearable, and biomedical systems are also highlighted. Lastly, current limitations and gaps in the research, such as broadband performance, mechanical flexibility, environmental stability, and standardization are defined to inform the creation of the next-generation composite shielding solutions. Ultimately, this review aims to provide insights to researchers and engineers to further develop and implement next-generation composite shielding solutions.*

Keywords: *Magnetic shielding, Electromagnetic interference (EMI) shielding, polymer composites, Carbon-based composites, Composite material design.*

1. Introduction

This section gives a background of the study, which includes the rising need to have efficient electromagnetic and magnetic shielding because of the rise in the number of electronic devices and wireless systems. It also explains rather briefly the shortcomings of traditional metallic shields and proposes polymer and carbon-based composites as a promising alternative. It further describes the gaps in the literature that exist and the purpose of the review that forms the basis of the comprehension of the performance, design strategies, and comparative assessment of composite shielding materials.

1.1. Background and Motivation

The shielding of magnetic and electromagnetic interferences (EMI) has gained even more significant importance in the recent past because of the fast increase in the number of electronic instruments, wireless communication systems, and sophisticated electronic infrastructures that emit electromagnetic radiations capable of disrupting the performance of electronics [1]. Electromagnetic pollution from these systems can lead to signal degradation, malfunction, and reduced reliability of electronic equipment [1, 2]. The principle of shielding effectiveness is that electromagnetic waves are reflected, absorbed, and re-reflected inside the shield to guarantee electromagnetic compatibility and system stability [2]. Besides electromagnetic shielding, magnetic shielding also plays a vital role since the low-frequency magnetic fields can also permeate electronic systems and disrupt sensitive instruments, and thus the combination of electromagnetic and magnetic shielding is also necessary to protect communication, medical, aerospace, and industrial technologies [2].

Traditional shielding materials include high-permeability alloys (e.g., mu-metal, permalloy, ferrites) for magnetic shielding and conductive metals (e.g., copper, aluminum, silver, stainless steel) for EMI shielding. High-permeability alloys provide a low-reluctance path for magnetic flux, effectively redirecting low-frequency fields, and are widely used in precision instruments, medical imaging systems, and magnetic sensor enclosures [3–5]. Conductive metals, on the other hand, shield electromagnetic waves through reflection and absorption mechanisms due to their high electrical conductivity and are widely applied in electronics, telecommunications, aerospace, and industrial enclosures [2]. However, conventional magnetic shielding materials are often bulky and temperature-sensitive, while conductive metals are heavy, prone to corrosion, and lack flexibility, limiting their use in compact and modern systems [2, 6].

In response, polymer- and carbon-based composites have emerged as promising alternatives due to their lightweight nature, corrosion resistance, mechanical flexibility, and tunable electrical properties [7, 8]. These materials can incorporate conductive fillers such as carbon nanotubes, graphene, and MXenes to achieve effective shielding while maintaining structural adaptability and processability [9]. As a result, they are increasingly used in aerospace, wearable, and portable electronic systems requiring multifunctional performance. However, achieving high shielding performance often requires increased filler loading or complex fabrication methods, which may increase production cost and reduce mechanical integrity [9].

1.2. Research Gaps

Despite the growing interest in composite materials developed for electromagnetic and magnetic shielding, current literature reviews remain limited in scope, often focusing on specific material types, frequency ranges, or fabrication methods. While polymer-based EMI shielding studies summarize mechanisms, preparation protocols, and applications [10], comprehensive evaluations of structural design strategies, filler optimization, and fabrication techniques remain sparse. Similarly, reviews of low-frequency magnetic shielding composites indicate a lack of systematic analysis of composite architectures and performance comparisons with conventional metallic shields [5]. Furthermore, there is limited discussion on broadband performance, environmental stability, mechanical flexibility, scalability of fabrication methods, and real-world applications, highlighting opportunities for future research that integrates material design, processing, performance, and application considerations. These gaps indicate a need for a holistic review that not only examines material design, performance, and fabrication strategies but also considers potential application contexts of composite shielding materials.

1.3. Objectives and Scope of This Review

The purpose of this literature review is to present a brief overview of the existing studies on composite materials in electromagnetic and magnetic shielding. Specifically, it seeks to:

1. Compare the shielding effectiveness of different composite structures across low-frequency magnetic and high-frequency EMI regimes.
2. Determine material design strategies and filler combinations that optimize performance while maintaining lightweight and flexible properties.
3. Review fabrication methods and structural architectures that influence microstructure, reproducibility, and shielding effectiveness.
4. Analyze the current application areas of composite shielding materials across different industries and devices.
5. Identify gaps in current literature, including broadband performance, environmental durability, standardization of measurement protocols, and practical applications, to guide future research and development of next-generation composite shields.

The scope of this review is limited to polymer- and carbon-based composite shielding materials and their comparison with conventional metallic and magnetic shielding systems. It focuses on material design, fabrication techniques, performance evaluation, and application-driven development rather than device-level circuit design or electromagnetic simulation methodologies.

2. Fundamentals of Electromagnetic and Magnetic Shielding

This section outlines the fundamental principles of magnetic and electromagnetic shielding, including the mechanisms responsible for field attenuation, the definitions of shielding effectiveness (SE) and shielding factor (SF), and the standard methods used to characterize shielding performance across low- and high-frequency regimes.

2.1. Magnetic Shielding: Flux Redirection and Eddy Current Mechanisms

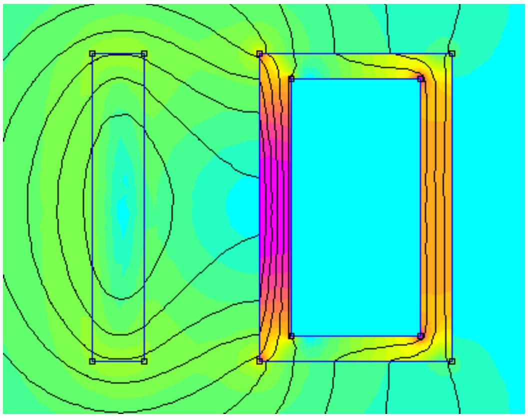


Figure 1: Illustration of magnetic flux redirection in a high-permeability shielding material, showing how external magnetic field lines are guided through the shielding layer instead of the protected region (Original figure by authors).

Magnetic shielding at low frequencies and static fields primarily relies on magnetic flux redirection (flux shunting). Figure 1, originally developed by the authors, illustrates how a high-permeability shielding material redirects magnetic flux lines away from the protected region. When a high-permeability material (μ) [H/m] is exposed to an external magnetic field, magnetic flux lines concentrate within the material because it provides a lower-reluctance path. Magnetic shielding at low frequencies relies primarily on permeability-dominated mechanisms, where the shield “guides” magnetic flux away from the protected region [5]. In this regime, attenuation mainly depends on material permeability and shield geometry.

For time-varying magnetic fields beyond the quasi-static regime, conductive materials develop eddy currents. These currents generate secondary magnetic fields that oppose the incident field according to Lenz's law, contributing to attenuation. However, at very low frequencies and near-DC conditions, the skin depth becomes large and eddy current effects weaken, making permeability the dominant shielding mechanism [5]. Magnetic shielding performance depends on the interplay between permeability, conductivity, and structural design, particularly in composite systems where these parameters can be tailored [3].

2.2. Electromagnetic Interference (EMI) Shielding: Reflection, Absorption, and Multiple Reflections

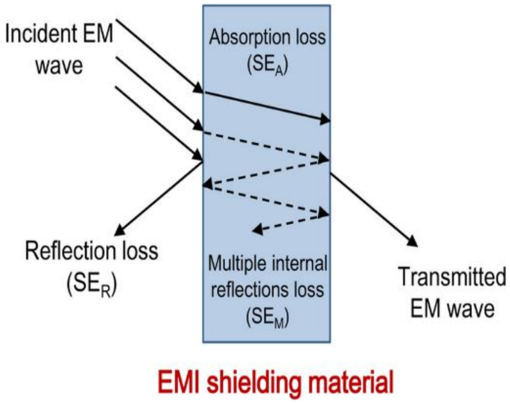


Figure 2: Representation of electromagnetic interference (EMI) shielding mechanisms, including reflection, absorption, and multiple internal reflections of incident electromagnetic waves within a shielding material (Reproduced from [5]).

At higher frequencies (kHz–GHz), EMI shielding mainly occurs through reflection, absorption, and multiple internal reflections, as illustrated in Figure 2 [5]. Reflection occurs because of impedance mismatch between free space and the shielding material; highly conductive materials contain mobile charge carriers that interact with incoming electromagnetic waves and lead to reflection on the surface. Reflection is described as arising from interactions between electromagnetic waves and free charge carriers within conductive media [1].

Absorption occurs when electromagnetic energy entering the material is dissipated by dielectric loss, magnetic loss, and ohmic (conductive) loss. The energy of the electromagnetic field is transformed into heat in the material volume through this process [1]. In heterogeneous or porous structures, waves may undergo multiple internal reflections, increasing the effective propagation path and enhancing attenuation before transmission. Structural and material parameters—such as conductivity, permittivity, permeability, and interfacial architecture—govern the dominance of reflection- or absorption-controlled shielding across different frequency regimes [3].

2.3. Quantification of Shielding Effectiveness

Shielding effectiveness (SE) describes the attenuation provided by a shielding material and is defined as the logarithmic ratio of incident to transmitted electromagnetic power. It is commonly expressed in decibels (dB) as:

$$SE_{dB} = 10\log_{10}\left(\frac{P_i}{P_t}\right) \tag{1}$$

where P_i is the incident power and P_t is the transmitted power [1]. When expressed in terms of electric or magnetic field amplitudes, SE may also be written as:

$$SE_{dB} = 20\log_{10}\left(\frac{E_i}{E_t}\right) \tag{2a}$$

$$SE_{dB} = 20\log_{10}\left(\frac{H_i}{H_t}\right) \tag{2b}$$

where E_i and H_i denote incident electric and magnetic field strengths, respectively, and E_t and H_t are their transmitted counterparts.

The classical model decomposes total shielding effectiveness into three contributions:

$$SE = SE_R + SE_A + SE_M \tag{3}$$

where SE_R represents reflection loss, SE_A represents absorption loss, and SE_M accounts for multiple internal reflections within the shielding material [1].

However, the multiple internal reflections term (SE_M) is not strictly positive and additive in all cases. For sufficiently thin shielding materials or at high frequencies where wavelength effects become significant, this term may become negligible or even negative due to phase cancellation and interference effects.

Shielding effectiveness (SE) is commonly used for high-frequency electromagnetic interference (EMI) shielding and is derived from electromagnetic wave transmission parameters. In contrast, shielding factor (SF) is typically used in low-frequency or quasi-static magnetic shielding applications and is defined as a dimensionless ratio of magnetic field strength in the unshielded region to that in the shielded region, and may be expressed either in terms of magnetic field intensity (H) or magnetic flux density (B), depending on the measurement method used, as shown in Equations (4a) and (4b):

$$SF = \frac{H_{\text{unshielded}}}{H_{\text{shielded}}} \tag{4a}$$

$$SF = \frac{B_{\text{unshielded}}}{B_{\text{shielded}}} \tag{4b}$$

While SE is usually expressed in decibels (dB) using power or field ratios obtained from network analyzer measurements, SF is often expressed as a linear ratio and measured using magnetometers or Hall-effect sensors [11]. The distinction is important because SE primarily characterizes wave attenuation in conductive and dielectric media, whereas SF describes flux attenuation in high-permeability materials under low-frequency magnetic field conditions.

Frequency strongly influences shielding behavior. In low-frequency applications, magnetic shielding is largely a matter of permeability and geometry, but in high-frequency applications, conductivity and skin-depth considerations take over. As frequency increases, skin depth decreases and absorption by conductive materials increases. It is emphasized that the dominant processes of low-frequency magnetic shielding and high-frequency EMI shielding differ radically, which should be characterized in relation to the frequency [5]. Consequently, the theoretical analysis of shielding materials must consider electromagnetic parameters with frequency dependence such as conductivity (σ) [S/m], permeability (μ) [H/m], and permittivity (ε) [F/m].

2.4. Characterization and Measurement Techniques

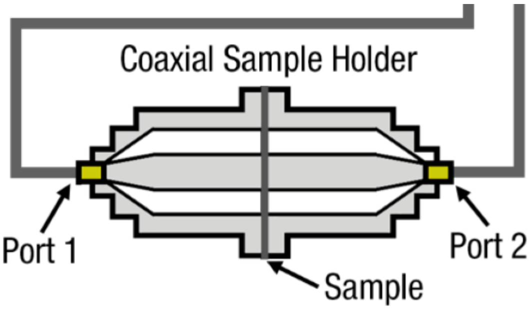


Figure 3: Coaxial transmission line setup used for measuring electromagnetic shielding effectiveness (SE) of planar materials (Reproduced from [12]).

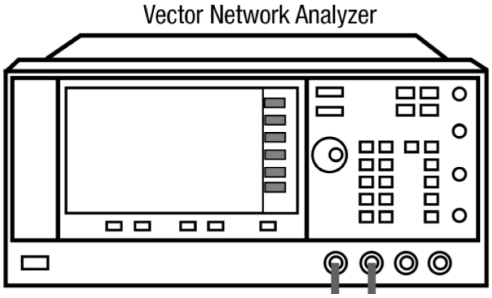
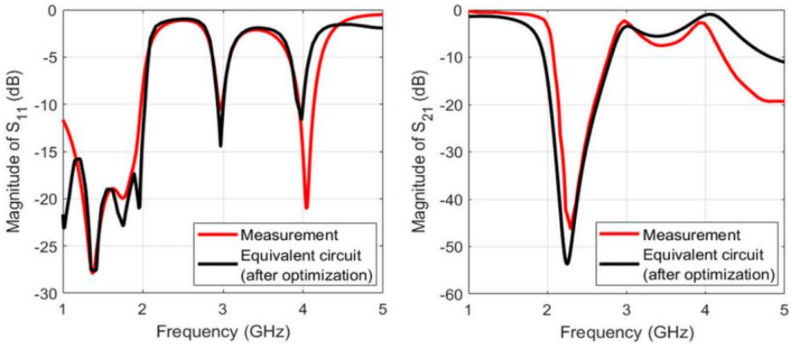


Figure 4: Vector Network Analyzer (VNA) measurement setup used to determine scattering parameters (S-parameters) for calculating shielding effectiveness and electromagnetic wave transmission characteristics of materials (Reproduced from [12]).

Shielding materials must be evaluated using standardized characterization methods to measure their usefulness in various frequency regimes. Shielding performance is usually described in shielding effectiveness (SE) units that quantify the attenuation of electromagnetic radiation as it passes through a substance [1]. Accurate SE quantification is necessary for com-



(a) (b)

Figure 5: S-parameter responses obtained from VNA measurements and simulations: (a) S_{11} (reflection coefficient) and (b) S_{21} (transmission coefficient), showing reflection and transmission characteristics of the material system (Reproduced from [15]).

paring material systems and validating design reproducibility.

EMI shielding materials are characterized using several experimental methods. The most common is the coaxial transmission line method (Figure 3) [12], which can be used to obtain precise and repeatable results within a wide frequency spectrum [13]. In this approach, the sample is inserted between coaxial fixtures and creates a transmission route through which electromagnetic waves travel, and the attenuation of the transmitted signal is measured to calculate shielding effectiveness [14]. The method is usually applied through standardized methods such as ASTM D4935 that guarantee uniformity of measurement conditions.

The other technique that is commonly used is the free-space measurement method that is well adapted to high-frequency applications at the microwave and millimeter-wave frequencies [1]. In this configuration, the transmitting and receiving antennas are mounted on opposite sides of the test material, and electromagnetic attenuation in open space is measured. This is a beneficial method for assessing large or non-uniform samples and is commonly applied in wireless communication and radar-related systems.

Shielding methods that are applied to assess shielding performance in controlled electromagnetic conditions include the shielded box and shielded room [13]. These methods include placing the material in a specified area and measuring the attenuation of the electromagnetic field within that area. These methods are especially applicable to system-level tests in which shielding performance has to be tested under realistic operating conditions.

The most important tool in these methods is the Vector Network Analyzer (VNA) (Figure 4) [12], which allows a high level of characterization of electromagnetic wave interactions with materials. The VNA measures scattering parameters (S-parameters) (Figure 5) [15], including transmission and reflection coefficients, which can be used to calculate shielding effectiveness [14]. In addition to amplitude, the VNA also provides phase information, allowing for the determination of complex electromagnetic properties such as permittivity and permeability [13].

Low-frequency magnetic shielding requires different measurement methods because the fields are quasi-static. These are typically evaluated using sensors such as fluxgate magnetometers or Hall-effect sensors, which measure the attenuation of magnetic flux density within a shielded region [1]. In these scenarios, performance is commonly stated in terms of a shielding factor (SF), and the difference between magnetic shielding and high-frequency EMI shielding values is emphasized.

A summary of the main characterization techniques, including their frequency ranges, setups, advantages, limitations, and applicable standards, is provided in Table 1.

Table 1: Comparison of Shielding Measurement Techniques.

Method	Frequency Range	Setup	Advantages	Limitations	Standard
Coaxial	kHz–GHz	Sample in coaxial line	Accurate, standardized	Limited to planar samples; requires precise sample fabrication and fixture compatibility	ASTM D4935
Free-space	MHz–GHz	Antennas	Non-contact, large samples	Sensitive to environmental reflections and alignment errors	IEEE 299
Shielded Box	Low–Mid freq	Enclosure	Realistic testing	Limited repeatability due to enclosure variability and edge effects	–
Shielded Room	Broad	Full enclosure	System-level evaluation	High cost, complex calibration, and facility dependence	–

Note: The "Shielded Box" and "Shielded Room" methods do not have a single universally adopted standard in the same way as coaxial or free-space methods; instead, they are typically implemented following system-specific test protocols depending on the enclosure design and measurement objective.

These characterization methods provide a basis for evaluating conventional and composite shielding materials.

3. Conventional Shielding Materials

Conventional shielding materials are widely used to regulate and confine magnetic fields for reliable system operation across various applications.

3.1. High-Permeability Alloys for Magnetic Shielding

High-permeability alloys are valued for combining high magnetic permeability with significant electrical resistivity [16]. This combination enables efficient attenuation of low-strength magnetic fields while reducing eddy current losses in AC power systems. Their ability to redirect low-level magnetic flux while minimizing energy dissipation makes them highly reliable. Some alloys also possess high saturation capacities, allowing their use in both high-power infrastructure and precision-sensitive instrumentation [17].

3.2. Conductive Materials for EMI Shielding

Conductive metals such as copper, aluminum, silver, and steel are widely used for electromagnetic interference (EMI) shielding due to their high electrical conductivity [18]. Their shielding mechanism primarily involves reflection and absorption caused by interactions between free charge carriers and electromagnetic fields.

These materials are widely used in consumer electronics, telecommunications, power systems, and aerospace structures because of their strong shielding performance and ease of manufacturing. However, their high weight, corrosion susceptibility, and limited flexibility restrict their use in lightweight and deformable electronic systems [19, 20].

In addition, their shielding performance is largely constrained by intrinsic material properties, where improvements in conductivity or durability may compromise weight or mechanical adaptability.

Table 2: Comparison of Conventional Magnetic and Electromagnetic Shielding Materials.

Material	Key Strengths	Primary Limitations	Typical Applications
Mu-metal	Exceptional permeability (up to 400,000); highest attenuation for weak fields.	Low saturation point (0.6–0.8 T); extremely sensitive to mechanical shock and requires specialized hydrogen annealing.	MRI rooms, sensitive scientific sensors, and aerospace navigation and satellite systems [20].
Silicon Steel	High saturation (1.6–2.0 T) and increased electrical resistivity to suppress eddy current losses in AC applications.	Lower permeability than nickel alloys; brittle at high silicon content and performance drops significantly above 1 kHz.	Power-frequency (50/60 Hz) transformers, electric motors, and generators.
General Ferromagnetic Metals (LCS/Iron)	Highest saturation capacity (∼2.2 T); robust structural strength and very cost-effective.	Low initial permeability; very heavy and highly prone to corrosion and rust if not properly coated.	Large-scale structural shielding, MRI suite outer walls, and high-intensity field containment.

Note: LCS refers to low-carbon steel.

3.3. Limitations of Conventional Materials and the Case for Composites

Despite their effective electromagnetic properties, conventional materials introduce significant engineering challenges. Their high density results in bulky shielding structures that complicate compact and portable system design. Their metallic composition also increases susceptibility to corrosion, requiring protective coatings and maintenance for long-term durability [19, 20]. Rigid fabrication processes and installation complexity further limit design adaptability compared with lightweight composite alternatives [17].

Table 2 summarizes the performance characteristics and primary limitations of various conventional shielding materials.

These limitations have driven the development of composite shielding materials with tunable electromagnetic properties enabled by engineered microstructures, hybrid fillers, and polymer matrices. Unlike conventional metals, composites enable simultaneous optimization of shielding effectiveness, flexibility, and weight reduction, making them strong candidates for advanced applications such as wearable electronics, aerospace systems, and flexible electromagnetic protection platforms.

4. Composite Shielding Materials: Design, Fabrication, and Performance

This section discusses the design principles, structural strategies, fabrication techniques, and shielding performance of composite materials across low-frequency magnetic and high-frequency EMI regimes.

4.1. Overview of Composite Shielding Materials

As demand for lightweight and flexible electronics grows, traditional metal shields are increasingly replaced by advanced material systems. Composite materials have emerged as the leading alternative to overcome the weight and corrosion limitations of conventional metals. Composite shielding materials are formed by incorporating magnetic or conductive fillers into non-conductive polymer matrices [1]. The polymer matrix, typically epoxy, polyurethane, or thermoplastic, serves as a flexible and processable backbone. Shielding performance is mainly provided by fillers such as metal nanowires, graphene, carbon nanotubes (CNTs), or magnetic ferrites [7]. Rather than uniformly mixing fillers, researchers engineer composite structures to optimize shielding performance and durability. For example, maximizing wave absorption can be achieved by stacking alternating layers of magnetic and conductive materials [1–7]. Other designs include porous aerogels, foams, and coated textiles for flexible shielding applications. These foam structures use internal air pockets to trap electromagnetic waves and promote repeated internal reflections before dissipation [22].

This tailored approach gives composites significant advantages over conventional metals. Their lightweight and corrosion-resistant nature makes them suitable for aerospace and portable electronics [7]. Their flexibility also enables integration into complex geometries. By adjusting filler concentration, material selection, and internal structure, engineers can even precisely adjust the material's shielding strength to block particular interference frequencies [23]. With the principles and advantages of composite materials established, attention now turns to the fabrication techniques that dictate their microstructure, filler dispersion, and overall shielding effectiveness.

4.2. Structural Design Strategies

Composite materials are widely used across various technologies because of their versatility [1]. Composites containing magnetic nanoparticles or amorphous ribbon coatings are effective against low-frequency magnetic interference, such as in wireless chargers or car sensors. In contrast, high-frequency EMI applications require absorption-dominant materials from devices like gigahertz radar and 5G networks. Lightweight carbon-based polymers are preferred because they shield sensitive circuits without adding bulk or generating secondary reflections [22, 23].

Table 3 summarizes common structural designs used in composite shielding systems. The table highlights their shielding mechanisms, engineering advantages, and inherent limitations.

With these structural design strategies established, the discussion now shifts to the fabrication techniques that govern filler dispersion, microstructural control, and the resulting electromagnetic performance of composite shielding systems.

4.3. Fabrication Techniques

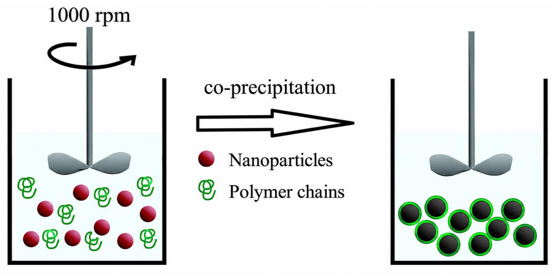


Figure 6: Schematic illustration for the solution blending method (Reproduced from [26]).

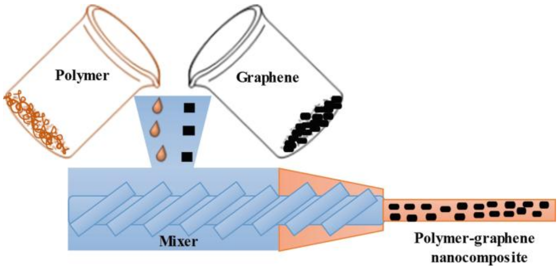


Figure 7: Schematic representation of the melt blending process used to incorporate conductive or magnetic fillers into a polymer matrix under elevated temperature and shear mixing conditions (Reproduced from [27]).

Fabrication methods directly affect composite microstructure, filler dispersion, mechanical integrity, and shielding effectiveness (SE). Various processing methods are used to integrate

Table 3: Structural Designs of Composite Shielding Materials.

Structural Design	Mechanism of Action	Key Advantage	Limitations
Stacked / Multilayer	Alternates impedance layers to induce progressive wave absorption [7].	Highly tunable SE for specific broadband frequencies.	Layer alignment complexity; potential interfacial delamination.
Coated Fabrics	Applies a conductive/magnetic layer over a flexible textile substrate.	Extreme flexibility; ideal for wearable electronics and cables.	Reduced durability under repeated bending or washing cycles.
Foams	Uses internal porous air pockets to force multiple internal wave reflections [22].	Ultra-lightweight; excellent for absorption-dominant high-frequency shielding.	Mechanical fragility; limited structural strength.
Porous Aerogels	Enhances wave scattering and absorption.	Ultra-low density; excellent broadband attenuation performance.	Brittle structure; challenging large-scale fabrication.

conductive and magnetic fillers into polymer matrices while preserving material performance. Representative fabrication methods include solution blending, melt blending, in situ polymerization, and advanced additive manufacturing techniques [1, 24, 25].

Solution blending (Figure 6) [26] is a common fabrication method for making polymer-based shielding composites, in which the conductive fillers are initially dispersed in a solvent and subsequently mixed with the polymer solution. After solvent evaporation, relatively uniform filler dispersion can improve electrical connectivity compared with melt processes [7]. It is particularly useful for temperature-sensitive polymers and applications requiring precise filler dispersion [7].

Another common technique is melt blending (or melt mixing), where fillers such as carbon nanotubes (CNTs), graphene, or metal nanoparticles are mechanically mixed into a polymer melt above its melting point, as illustrated in Figure 7 [27]. The process promotes filler dispersion through shear mixing and is compatible with industrial thermoplastic processing [26]. However, high filler loadings require optimized mixing conditions to prevent agglomeration and maintain processability [28].

In situ polymerization involves polymerizing monomers in the presence of dispersed fillers, and it can help increase interfacial adhesion and minimize filler aggregation. It was demonstrated that this approach yields better electrical and mechanical properties of the composites because the polymer chains are formed around well-dispersed filler particles [1]. Reaction kinetics and filler surface chemistry must be controlled to prevent phase separation.

Recently, additive manufacturing (3D printing) has emerged as a fabrication method for complex shielding composites [24]. Controlling deposition patterns and filler alignment enables gradient or anisotropic filler distributions. For example, Fused Filament Fabrication (FFF) polymer-based composites that can be 3D printed, as illustrated in Figure 8 [29], allow precise layer-by-layer microstructural control that can improve shielding performance compared with conventional processing methods [6].

Other techniques such as electrospinning and freeze drying create composites with unique structural characteristics. Electrospinning produces fibrous mats with oriented conductive pathways, offering enhanced electrical networks at low filler loadings [1]. Freeze drying creates porous interconnected structures that enhance absorption-dominant shielding through multiple internal reflections [7].

With the description of the fabrication techniques completed, the next analysis of composite materials is centered on the real performance of composite materials in low-frequency magnetic applications and high-frequency EMI shielding.

4.4. Performance at Low-Frequency and DC Magnetic Fields

DC and low-frequency magnetic shielding composites rely on enhanced permeability and magnetic flux redirection through engineered structures. A metamaterial composite combining mu-near-zero (MNZ) media with a patterned ferrite slab demonstrated a maximum shielding effectiveness (SE) of 20.56 dB at 85.5 kHz, which was approximately 19 dB higher than a single ferrite slab of the same thickness [30]. The MNZ layer concentrated magnetic flux while the patterned ferrite minimized leakage into the protected region. This demonstrates the effectiveness of combining permeability control with flux shaping in low-frequency shielding.

Layered composite designs provide another approach for optimizing low-frequency shielding. In one study, a multi-layer composite shielding box achieved shielding factors (SF) of 593.5 for static fields and 652.8 at 1 kHz, with a total thickness of 2.3 mm [31]. The multilayer structure enabled the magnetic flux to pass through sequential layers of customized permeability, thereby reducing leakage and effectively containing the field. This demonstrates that multilayer structures can achieve higher attenuation than single-layer composites of similar composition. It also emphasizes the significance of layered design and optimization of thickness in the case of low-frequency magnetic shielding.

Furthermore, hybrid composites combining ferrite fillers with conductive polymer matrices provide a complementary approach, achieving stable low-frequency performance while enabling additional effects at slightly higher frequencies. One such composite maintained SE around 18 dB below 20 kHz, with SE increasing at higher frequencies due to eddy currents induced in the conductive phase [32]. This hybrid design combines permeability-based flux redirection with conductivity-enhanced absorption and is appropriate for quasi-static fields, with the added benefit of flexibility and light weight. This example highlights how combining magnetic and conductive phases in a polymer matrix can broaden the functional range of low-frequency shielding composites.

Table 4 shows that shielding performance depends strongly on material composition, structural design, and operating frequency. The table demonstrates that structural design, constituent selection, and frequency regime are all important factors in determining the SE or SF of composite materials. These results highlight the versatility of composites in providing lightweight, tunable, and high-performance magnetic shielding for DC and low-frequency systems.

4.5. Performance at High-Frequency EMI

At high frequencies (MHz–GHz), composite materials exhibit excellent EMI shielding through conductive networks, magnetic fillers, and engineered microstructures. For example, a hierarchical porous carbon nanotube/carbon composite achieved an EMI shielding effectiveness (SE) of 61.4 dB across broad frequency ranges in the radiofrequency domain, showing enhanced attenuation compared to non-porous carbon systems [33]. A low filler concentration (2.2 vol per cent CNT) produced an SE of 47.0 dB in the X-band frequency range (approximately 8–12 GHz) in segregated carbon nanotube/polydimethylsiloxane (CNT/PDMS) composites because of the effective conductive pathways and interfacial reinforcement [34].

Other engineered composites have achieved even higher SE values. A carbon nanotube film embedded with copper nanoparticles exhibited approximately 248 dB shielding at an ultrathin film thickness of approximately 15 µm,

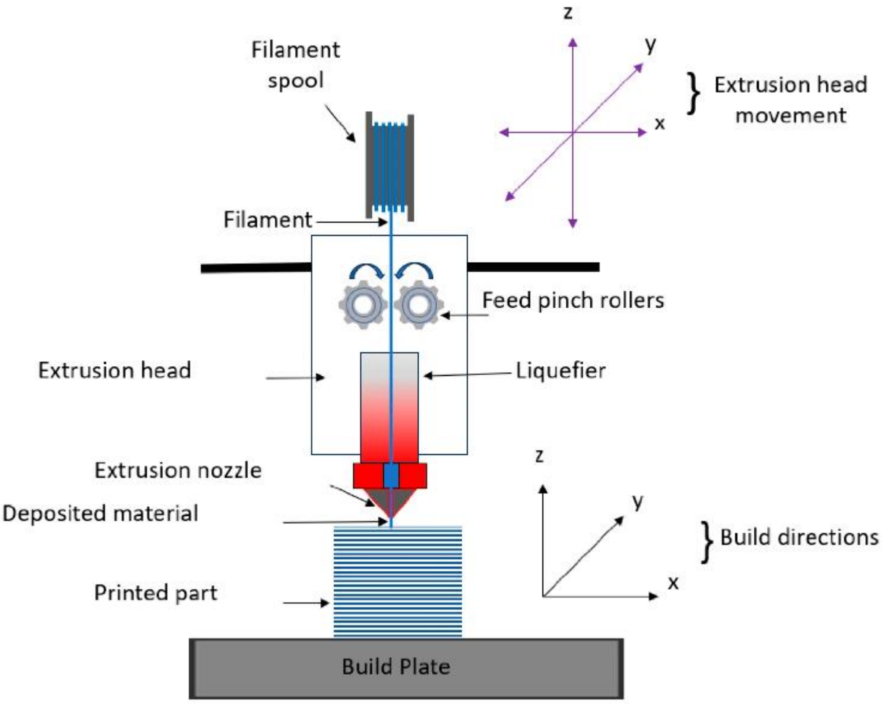


Figure 8: Schematic of fused filament fabrication (FFF) 3D printing process used to fabricate polymer-based composite shielding structures with controlled layer-by-layer deposition and filler alignment (Reproduced from [29]).

Table 4: DC / Low-Frequency Composite Shielding Performance.

Composite System	**Frequency**	**SE (dB) / SF**	**Structure**
MNZ + Patterned Ferrite	85.5 kHz	20.56 dB (↑19 dB vs. ferrite)	Metamaterial: MNZ + patterned ferrite slab
Multi-Layer Composite Box	0–1 kHz	SF ≈ 593–653	Stacked layers with tailored permeability
Ferrite-Fiber + Conductive Polymer	< 20 kHz	$\sim$18 dB	Hybrid: ferrite fillers + conductive polymer

Note: MNZ (mu-near-zero) refers to metamaterial structures with near-zero effective magnetic permeability, enabling enhanced magnetic flux manipulation and shielding performance. SF (shielding factor) is a dimensionless ratio defined as the magnetic field strength in the unshielded region divided by that in the shielded region.

fabricated via an electrodeposition-assisted process [35]. The reported value was obtained under controlled experimental conditions using engineered CNT film architectures combined with copper nanoparticle deposition, which promoted a highly continuous conductive network and strong interfacial contact between phases. In addition to its shielding performance, the same study reported excellent mechanical reliability under repeated bending cycles, attributed to the structural integrity of the composite film.

Hybrid systems using carbonyl iron powder (CIP) and carbon fabric in a polymer matrix were found to achieve 120 dB shielding in the Ka-band (26–40 GHz), indicating the effectiveness of combining magnetic and conductive fillers in broadband EMI shielding systems [25].

Table 5: High Frequency EMI Shielding Performance of Composites.

Composite System	**Target Frequency**	**Reported SE (dB)**	**Key Features**
Hierarchical porous CNT/carbon [33]	RF range	61.4 dB	3D porous conductive network with enhanced wave scattering
Segregated CNT/PDMS [34]	X-band (~8–12 GHz)	47.0 dB	Low filler loading; percolated conductive pathways
CNT/Cu nanoparticle film [35]	RF/μwave	~248 dB	Nanocomposite conductive film with electrodeposited Cu nanoparticles
CIP + carbon fabric composite [25]	Ka-band (26–40 GHz)	120 dB	Hybrid magnetic + conductive fillers
MXene hybrid films (P-Co-MX) [36]	~8.2 GHz	61.9 dB	2D layered conductive network enabling interfacial polarization and reflection loss

Note: The reported ~248 dB SE was obtained from ultrathin CNT/Cu nanoparticle films under controlled laboratory conditions with engineered conductive network architectures.

A comparison across representative composite systems is provided in Table 5, showing SE performance trends in different frequency bands and material configurations.

Across these examples, composites routinely achieve $SE > 40$ dB, which corresponds to more than 99.99% attenuation of incident electromagnetic power, while also offering advantages such as lightweight form factors, flexibility, and tunable structures. The ultrahigh shielding effectiveness of nanocomposite films highlights the potential of nanoscale conductive networks for high-frequency EMI shielding. When magnetic fillers (e.g., carbonyl iron) are combined with conductive fabrics, broadband attenuation across GHz bands can be achieved, making these materials promising for 5G communication, sensors, and portable electronics.

The demonstrated performance of these composites across various frequencies underscores their suitability for practical applications in aerospace, wearable, biomedical, and communication systems.

5. Applications of Composite Shielding Materials

The composite shielding materials are no longer considered as mere laboratory curiosities but rather offer viable solutions in many industries due to their lightweight, flexible, corrosion-resistant, and EMI-attenuating properties. These features render them highly applicable in electronics, aerospace, wearable, and healthcare systems.

5.1. Aerospace and Defense Systems

In aerospace and defense applications, composite shielding materials offer a critical advantage by significantly reducing structural weight while maintaining effective protection against electromagnetic interference (EMI) in sensitive avionics, radar, and communication systems. Their performance can be tailored through structural design and filler selection to meet stringent requirements for mechanical durability, thermal stability, and broadband electromagnetic attenuation, making them suitable for high-performance and mission-critical environments [37].

5.2. Consumer Electronics and Portable Devices

Composite shielding materials are widely applicable in consumer electronics and portable systems, where compactness, lightweight design, and signal integrity are essential. Polymer-based composites incorporating conductive fillers, layered architectures, or flexible conductive fabrics are particularly effective in mitigating EMI in the MHz–GHz frequency range without compromising device portability. These materials are commonly integrated into smartphones, laptops, and wireless communication modules to reduce electromagnetic noise and improve device reliability [2].

5.3. Wearable and Flexible Electronics

Wearable and flexible electronics require shielding materials that can conform to dynamic mechanical deformation while maintaining stable electromagnetic performance. Composite systems based on elastomeric polymers combined with conductive or magnetic fillers enable stretchable, bendable, and lightweight EMI shielding solutions. These materials are increasingly used in smart textiles, health-monitoring wearables, and flexible sensors, where both mechanical compliance and consistent shielding effectiveness are required [38].

5.4. Biomedical and Healthcare Systems

In biomedical applications, EMI shielding is used to assure the proper operation of sensitive medical devices by eliminating the effect of stray electromagnetic fields. Medical enclosures, wearable health monitors, or implantable devices can be made using light and flexible polymer composites without carrying the weight of metal shielding. Certain uses are shape-memory integrated composites applicable to the exact medical apparatus like pacemakers where EMI shielding is important to the safety of the device and the welfare of the patients [39].

Although these applications are promising, there are some challenges that have yet to be overcome to ensure full realization of the potential of composite shielding materials in real world situations.

5.5. Current Limitations and Research Gaps

Despite their promising performance, composite shielding materials face several practical and scientific challenges. Manufacturing complexity is a primary issue: high-performance composites often require controlled dispersion and alignment of fillers, which are difficult to reproduce at scale. The ability to produce uniform filler dispersion and uniform microstructure remains a major challenge that limits reproducible fabrication, scalability, and industrial adoption while increasing production costs [40]. Another key challenge is the trade-off between functional performance and mechanical properties. High filler loadings can improve electrical conductivity or magnetic permeability but often reduce flexibility and toughness. Mechanical flexibility and shielding performance tend to be negatively correlated, making design optimization particularly challenging for flexible and wearable applications [32].

Frequency-dependent performance remains an important research gap. Much of the literature reports strong shielding performance within specific frequency bands, whereas broadband behavior is not always well understood [41]. Comparative studies spanning wide frequency ranges are limited, restricting the understanding of broadband shielding performance. Furthermore, environmental durability remains insufficiently explored. The relatively small number of studies investigating long-term environmental stability, particularly under real-world operating conditions, limits the practical applicability of composite shielding materials in diverse environments.

Lastly, there are the economic and standardization problems. Most of the high-performance composites are based on costly nanofillers and energy-consuming fabrication, which casts doubt on cost-effectiveness and sustainability. The non-uniform measurement protocols also make it more difficult to directly compare materials and studies, as non-uniform measurement and reporting protocols hinder direct comparison [42]. To bridge these gaps, it is necessary to improve the composite shielding materials that have been studied in the laboratory for practical applications.

5.6. Future Research Directions

Future research in composite shielding materials should focus on bridging the gap between laboratory-scale performance and real-world applicability. One key direction is the development of scalable and controllable fabrication methods that provide uniform filler dispersion and reproducible microstructures at an industrial scale.

Another important direction is the development of multifunctional composites that combine electromagnetic shielding with additional functionalities such as thermal management, mechanical sensing, structural reinforcement, and energy storage. This would allow for new materials that can be used in integrated electronic systems.

Broadband and adaptive shielding materials also represent a significant research opportunity. Future composites should be designed for frequency-tunable or self-adaptive shielding over broad frequency ranges, including dynamic electromagnetic environments, rather than frequency-limited performance.

Moreover, improved standardization of testing methods and reporting formats is essential to ensure comparability among studies and accelerate material development. Finally, the factor of sustainability, including the use of low-cost, recyclable, or bio-based matrices and fillers, will become increasingly important in future composite shielding research.

6. Conclusion

This review examined the progression of electromagnetic and magnetic shielding materials from conventional metals such as mu-metal, silicon steel, and ferromagnetic alloys to modern polymer-based composites. Conventional materials remain effective due to their high permeability and conductivity, but they are limited by weight, rigidity, corrosion susceptibility, and restricted design flexibility. In contrast, composite shielding materials offer tunable electromagnetic performance, enabling efficient shielding across both low-frequency magnetic fields and high-frequency EMI through engineered microstructures and hybrid filler systems.

Among the most promising designs identified are multilayer structures, porous and foam-based architectures, and hybrid composites combining conductive and magnetic fillers. In terms of fabrication, solution blending, melt processing,in situ polymerization, and additive manufacturing are key methods that strongly influence filler dispersion and final shielding effectiveness, with 3D-printing approaches showing particular potential for structural control and performance optimization. Despite these advances, several challenges remain, including achieving scalable and reproducible fabrication, balancing mechanical flexibility with shielding performance, ensuring broadband performance and long-term environmental stability, and establishing standardized testing and reporting protocols for consistent comparison across studies.

Overall, composite shielding materials represent a promising direction for next-generation electromagnetic protection systems. Continued developments are expected to enable lightweight, multifunctional, and application-specific shielding solutions for advanced electronics, aerospace, biomedical, and communication technologies.

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