Electromagnetic Shielding Performance of Carbon Fiber Reinforced Polymer Composites for Aerospace Structural Applications

Osman Fatih DAMNALI
Çanakkale Onsekiz Mart University

Volkan ESKİZEYBEK
Çanakkale Onsekiz Mart University

Hüseyin ARIKAN
Necmettin Erbakan University

To Cite This Chapter:
Damnalı, O. F., Eskizeybek, V., & Arıkan, H. (2025). Electromagnetic shielding performance of carbon fiber reinforced polymer composites for aerospace structural applications. In F. Z. Saltan, H. Arıkan, & Y. Uzun (Eds.), *Current studies in basic sciences, engineering and technology 2025* (pp. 13–48). ISRES Book Series. ISRES Publishing.

Introduction

The aerospace industry is a multidisciplinary field that involves designing, manufacturing, and operating aircraft and spacecraft. It is characterized by strict requirements for high performance, reliability, and safety. Systems and components used in this sector must demonstrate high structural accuracy and electronic stability to ensure consistent and safe operation (Parveez et al., 2022; Siengchin, 2023). Materials used in aerospace applications need to withstand harsh environmental conditions encountered during flight, such as high temperatures, pressure changes, vibration, radiation, and rapid thermal shifts. Given the demands of long-duration missions and high-speed operations, material properties like low density, mechanical strength, and thermal stability are critically important. In addition to engineering factors, considerations such as cost, availability, and maintainability also play a key role in selecting suitable materials for aerospace structures (Xia, 2023).

Within this context, materials used in aerospace structures are chosen by balancing their strength, density, temperature resistance, and manufacturability. Traditionally, aluminium, titanium, and steel alloys have been the main engineering materials in aircraft and spacecraft construction. Aluminium alloys, due to low density, excellent formability, and high specific strength, are commonly employed in fuselage panels, wings, and outer skins. Titanium alloys, characterized by a superior strength-to-weight ratio and resistance to corrosion and high temperatures, are preferred for engine components, landing gear parts, and critical joints. Steel, on the other hand, is mainly employed in load-bearing components and structural connectors that require exceptional hardness and fatigue resistance. However, these traditional metallic materials also have inherent limitations, including susceptibility to corrosion, high density, and high production costs (Hirankittiwong et al., 2025). Therefore, the search for lightweight, durable, and multifunctional alternatives has gained momentum in recent years.

Driven by goals such as weight loss, fuel efficiency, and performance improvement, carbon fiber reinforced polymer (CFRP) composites have become advanced materials for modern aerospace and space platforms. CFRP composites are lightweight, structurally efficient materials that deliver excellent mechanical properties, including high strength, fatigue resistance, and low density (Hamzat et al., 2025). Because of these benefits, CFRPs provide higher specific performance than traditional metallic structures and are increasingly used in aerospace engineering. Blends of carbon, glass, or aramid fibers embedded in polymer matrices offer notable strength, corrosion resistance, design flexibility, and weight savings. In particular, continuous carbon fiber reinforced composites are commonly used in key structural parts, such as fuselage panels, wings, tail sections, and satellite components (Hirankittiwong et al., 2025; Maria, 2013). Additionally, the natural electrical conductivity of carbon fibers allows CFRP composites to provide electromagnetic interference (EMI) shielding, improving the reliability of avionics, radar, and communication systems. As a result, CFRPs are viewed as multifunctional materials that combine high mechanical performance with electromagnetic protection in today's aerospace structures (W. Dong et al., 2025).

The rapid advancements in nanotechnology and digital communication—especially the widespread adoption of 5G networks—have further integrated electronic systems into aerospace structures. Modern aircraft and spacecraft feature numerous electronic devices, including radar systems, communication modules, power lines, and precision sensors (Prekodravac Filipovic et al., 2025). During operation, these devices emit electromagnetic waves (EMW), which contribute to EMI and radiation pollution. The increasing density of EM sources threatens the stability and reliability of aerospace systems, especially in high-frequency communication environments (X. Y. Wang et al., 2022). Therefore, the use of high-performance electromagnetic shielding (EM-shielding) materials has become essential. Thanks to their light weight, high mechanical strength, and design flexibility, CFRP-based composite materials offer an ideal solution for meeting both structural and EMI protection needs. CFRP composites with wide effective absorption bandwidths (EAB), high absorption capacity, and thin matching thicknesses not only ensure the reliable operation of onboard electronics but also help protect human operators from the harmful effects of electromagnetic radiation (Suresha et al., 2024).

The main goal of this study is to thoroughly evaluate the electromagnetic shielding effectiveness (EMSE) of CFRP composites used in aerospace structures. It also evaluates the mechanical and environmental performance of these materials and examines their EMI shielding capabilities, providing insights for the development of next-generation multifunctional composites.

1.Fundamentals Of EMI Shielding

This section presents a comprehensive overview of the fundamental principles governing electromagnetic interference (EMI) shielding in advanced composite materials. It begins by introducing the essential characteristics of electromagnetic waves and describing their interaction with matter through reflection, absorption, and transmission phenomena. The discussion then addresses the physical mechanisms that determine shielding effectiveness, highlighting the parameters that influence electromagnetic attenuation in CFRP composites. Particular emphasis is placed on experimental evaluation approaches—such as EMI shielding measurements and analytical calculations—that enable the quantitative assessment of material performance. Furthermore, the dielectric and magnetic behaviours of the composites are analysed to elucidate their contributions to energy storage, dissipation, and loss mechanisms. Collectively, these discussions establish the theoretical and experimental foundation required to understand and optimize the EMI shielding performance of CFRP composites employed in aerospace structural systems.

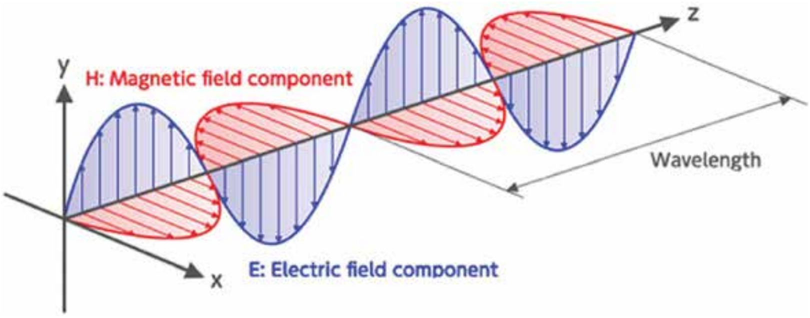
1.1.Electromagnetic Waves

Electromagnetic waves are transverse waves that transmit energy, resulting from the oscillation of magnetic and electric fields in mutually perpendicular planes. These waves are generated by the simultaneous interaction of magnetic and electric fields and can travel through a vacuum at the speed of light without requiring a physical medium, as shown in Figure 1 (Kruželák et al., 2021). The primary sources of electromagnetic wave production are the acceleration of charged particles or changes in their energy states. Electromagnetic waves display both wave-like and particle-like characteristics; therefore, energy can be transferred either as a continuous wave or as discrete packets called photons (Wdowiak et al., 2017).

The wave impedance describes the ratio between the magnitudes of the electric and magnetic fields, determining how energy is transmitted through the propagation medium. In free space, the intrinsic impedance is about 377 Ω, representing the characteristic impedance of the two fields (Rouhi et al., 2022). Far from the source, the wave shows typical behavior in the far-field region. Near the source, complex interactions among different field components create the near-field region. Based on their wavelength and frequency, electromagnetic waves are classified within the electromagnetic spectrum, which ranges from radio waves and microwaves to infrared, visible light, ultraviolet, X-rays, and gamma rays. Although electromagnetic waves do not lose energy as they propagate through space, they can undergo reflection, absorption, or conversion to other forms when interacting with matter (Zheng, Wang, Wang, et al., 2024).

Figure 1

Schematic Illustration of an Electromagnetic Wave

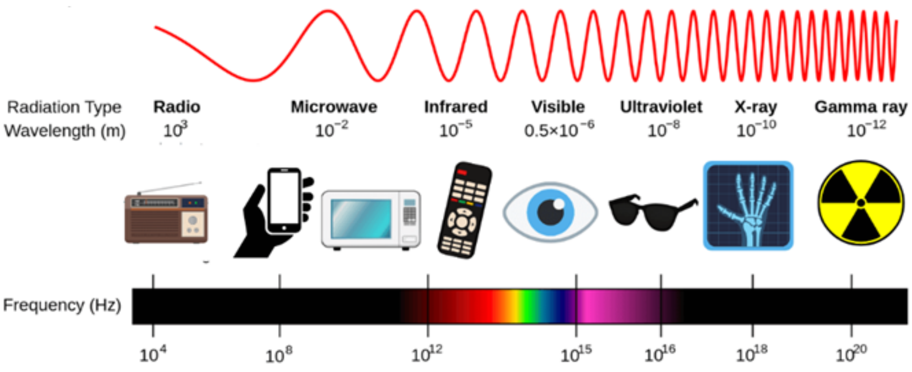


1.2.Electromagnetic Spectrum

The electromagnetic spectrum covers a wide range of frequencies—from radio waves to gamma rays—each region exhibiting distinct energy levels and interaction characteristics depending on its wavelength and frequency (Dungani Rudi et al., 2018). These frequency differences are vital for assessing EMI risk, especially in electronic and communication systems. As illustrated in Figure 2, Low-frequency radio waves can cause long-distance interference, while high-frequency microwave and terahertz waves produce short-range but more powerful interference effects. Therefore, the effectiveness of EMI shielding depends strongly on selecting materials and design strategies that correspond to the target frequency band. For instance, thin metallic layers or conductive polymer composites are commonly employed for shielding high-frequency electromagnetic waves, while thicker conductive or magnetic materials are more suitable for mitigating low-frequency interference (Mishra et al., 2018). As a result, understanding the distribution of frequencies across the electromagnetic spectrum is essential for selecting proper materials and designing structures in EMI shielding applications.

Figure 2

Electromagnetic Spectrum

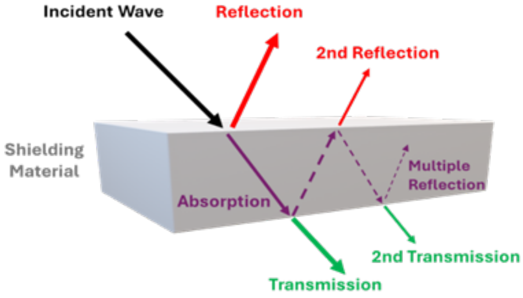


1.3.Mechanism of EMI Shielding

EMI shielding involves reducing the transmission of electromagnetic waves through space by using suitable shielding materials, thus protecting objects from incident radiation (Mishra et al., 2018).To explain the shielding performance observed in experimental studies, researchers have proposed several theoretical approaches, including electromagnetic field theory, eddy-current theory, and transmission line theory. Among these, transmission line theory has been widely accepted due to its computational simplicity, physical clarity, and high predictive accuracy (Hlo, 2021). According to this theory, when an electromagnetic wave interacts with a shielding material, three main mechanisms—reflection, absorption, and multiple reflections—contribute to its overall effectiveness. These mechanisms form the core principles of EMI shielding design and offer a critical framework for understanding how material choice, layer thickness, and structural configuration impact shielding performance (Tian et al., 2023).

Figure 3

Schematic Illustration of the EMI Shielding Mechanisms



1.3.1.Reflection

Reflection is a fundamental electromagnetic shielding mechanism in which a significant portion of incident electromagnetic energy is scattered back when waves strike a surface with high electrical conductivity. Free charge carriers on the surface—primarily electrons—interact with the electric-field component of the incoming wave, reflecting most of the electromagnetic energy outward (Hlo, 2021)

The effectiveness of reflection depends not only on the material's electrical conductivity but also on the impedance mismatch between adjacent media. The greater the impedance difference, the larger the fraction of energy reflected. Materials with high electrical conductivity enhance this mismatch and thereby strengthen reflection (Tian et al., 2023)

In this context, the percolation threshold is essential for understanding reflection behavior in composite systems. It represents the critical filler concentration at which conductive particles form continuous networks within the matrix. Once this threshold is exceeded, the material becomes macroscopically conductive, enabling efficient reflection of incident electromagnetic waves. As a result, composites designed above the percolation threshold show significantly better reflection-based shielding performance.

The degree of reflection is also influenced by the material’s magnetic permeability (μ). As permeability approaches the vacuum value, resistance to wave propagation decreases; however, when permeability is low and conductivity is high, energy loss primarily occurs through reflection (Ismail & Azis, 2024). A combination of high conductivity and low permeability provides optimal reflection-dominated EMI protection. Therefore, aluminium alloys and conductive polymer composites—commonly used in aerospace structures—are ideal materials for reflection-based EMI shielding.

1.3.2.Absorption

Absorption is a dissipation mechanism in which incident electromagnetic waves penetrate a material and convert most of their energy into heat through electrical and/or magnetic losses. This process is associated with several physical phenomena, including the formation of conductive networks, dipole polarization, magnetic resonance, and eddy currents (Parvez et al., 2025).

To enhance absorption efficiency, materials are often reinforced with magnetic fillers such as Fe_3O_4, ferrites, Ni, and their alloys, along with electrically conductive nanofillers like MXene, carbon nanotubes (CNTs), and graphene. The thickness of the material also plays a crucial role: increasing thickness lengthens the wave’s propagation path within the medium, thereby boosting energy attenuation (Yao et al., 2021). However, the optimal thickness must be selected carefully to ensure frequency and impedance matching; otherwise, surface reflections can become dominant, decreasing absorption efficiency.

The dielectric loss (ε'') and magnetic loss (μ'') components are the main factors that determine absorption performance. Therefore, structures that focus on absorption are usually designed as multiphase, micro- or nanoscale composite systems (Tian et al., 2023).

In aerospace applications, this mechanism is used to suppress radar waves, protect electronic components, and isolate signals. Specifically, Fe- and Ni-based alloys, along with CFRP composites, are suitable for applications that require both structural strength and electromagnetic performance.

1.3.3.Multiple Reflection

Multiple reflection is a secondary attenuation mechanism in which electromagnetic waves are repeatedly reflected and attenuated within a material through interactions with microscopic surfaces, pores, phase boundaries, or layered structures (Hlo, 2021). Although not the primary mechanism, it boosts overall EMI attenuation by increasing reflection- and absorption-related energy losses. Low-density, porous, or multiphase structures are especially effective in encouraging this behaviour, as the longer propagation path within the material allows the wave to lose more energy with each reflection.

Accordingly, the multiple-reflection effect increases with increasing material thickness; however, to ensure absorption remains dominant, the thickness must be optimized to prevent impedance-matching disruption (Yao et al., 2021)

In aerospace structural systems, this mechanism is often incorporated using micro- or mesoporous materials such as carbon foams, CNT networks, and MXene/ceramic hybrid layered composites. Thanks to their lightweight nature and high surface area, these materials both improve multiple reflections and provide mechanical stability under load.

1.4.EMI Shielding Effectiveness (EMI SE)

EMI shielding involves using engineered materials to reduce electromagnetic disturbances (EMD) and protect sensitive systems from external radiation. The effectiveness of these materials is usually measured by the electromagnetic shielding effectiveness (EMI SE) parameter, which indicates the amount of incident electromagnetic energy blocked, typically expressed in decibels (dB).

Theoretically, the EMI shielding efficiency of conductive materials can be estimated using the Simon formulation in Equation (1):

$$SE = 50 + \log\left(\frac{\sigma}{f}\right) + 1.7t\sqrt{\sigma f} \tag{1}$$

Where σ is the electrical conductivity (S•cm^{-1}), f is the frequency of the electromagnetic wave (MHz), and t is the thickness of the shielding layer (cm). This expression indicates that EMI SE increases with higher electrical conductivity and material thickness.

At a specific point relative to the radiation source, shielding effectiveness can also be expressed as Equation (2):

$$EMI\ SE = 10\ log\left(\frac{P_i}{P_t}\right) = 20\ log\left(\frac{E_i}{E_t}\right) = 20\ log\left(\frac{H_i}{H_t}\right) \tag{2}$$

Where P, E, and H represent the power, electric field strength, and magnetic field strength of plane waves, with subscripts i and t indicating incident and transmitted waves, respectively (Kruželák et al., 2021).

When an electromagnetic wave hits a shielding material, three main attenuation mechanisms happen:

(i) Reflection (SER) at the surface caused by impedance mismatch.

(ii) Absorption (SEA) within the bulk caused by ohmic and magnetic losses, and

(iii) Multiple reflections (SEM) between internal interfaces.

The total shielding effectiveness (SET) is described as the sum of these components.

According to Schelkunoff's theory, the total EMI shielding effectiveness (SET) is defined as the sum of three primary attenuation mechanisms that decrease electromagnetic wave transmission: reflection loss (SER), absorption loss (SEA), and multiple reflection loss (SEM) (Tian et al., 2023). As shown in Equation (3), this relationship can be written as:

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

Reflection loss primarily arises when a wave experiences an impedance discontinuity between free space and the surface of the shielding material. Based on plane-wave propagation principles, the SER is governed by the material's electrical conductivity (σ), magnetic permeability (μ), and the frequency (f) of the incoming electromagnetic wave, as expressed in Equation (4).

$$SE_R = 20\log\left(\frac{Z_i}{4Z_s}\right) = 39.5 + 10\log\left(\frac{\sigma^2}{\pi f \mu}\right) \tag{4}$$

Where Zi and Zs represent the impedances of free space and the shielding material, respectively. Here, σ, μ, and f denote the electrical conductivity, magnetic permeability, and frequency of the electromagnetic wave (Chen et al., 2024).

Absorption loss occurs when electromagnetic energy is converted into heat through interactions with mobile charge carriers, dipoles, and magnetic domains. It can be expressed as Equation (5):

$$SE_A = 20\frac{t}{\delta}\log e = 8.68\frac{t}{\delta} \tag{5}$$

Where t is the material thickness and δ is the skin depth, which is defined by (6):

$$\delta = \sqrt{\frac{1}{\pi f \mu\sigma}} \tag{6}$$

Thus, absorption loss is directly affected by the material’s thickness (t), conductivity (σ), magnetic permeability (μ), and frequency (f) (Tian et al., 2023).

Multiple reflection loss occurs when electromagnetic waves are repeatedly scattered within a material at multiple internal interfaces.

$$SE_M = 20\,log\left(1 - e^{-2t/\delta}\right) \tag{7}$$

Alternatively, it can be expressed in terms of SEA as:

$$SE_M = 20\,log\left(1 - 10^{-SE_A/10}\right) \tag{8}$$

For thin materials (t < δ), internal reflections extend the propagation path, increasing total EMI SE. In contrast, for thick materials (t > δ), most of the incident energy is absorbed, and multiple reflections become insignificant. This trend is shown in Figure 4.

Figure 4

Variation of Multiple Reflection Loss (SEM) with t/δ Ratio

Therefore, most studies in the literature tend to overlook the SEM component when dealing with relatively thick shielding materials, and they usually evaluate the total EMI SE solely based on the contributions of SER and SEA (Manjunath & Virupaxi, 2025; Tian et al., 2023).

1.5.Specific EMI Shielding (SSE)

Assessing the EMI shielding capability of a material requires consideration of more than its overall shielding effectiveness (SE); the physical attributes of the material—

particularly its density (ρ) and thickness (t)—also play an essential role. For this reason, the parameter known as specific shielding effectiveness (SSE) is used to represent the shielding efficiency normalized by either mass or thickness. This metric is widely regarded as a key engineering indicator for evaluating lightweight yet highly effective materials. SSE not only reflects the inherent shielding performance of a material but also underscores beneficial features such as reduced weight and minimal structural thickness (X. Y. Wang et al., 2022).

In porous or foam-structured materials, the bulk density directly impacts shielding performance. For these systems, SSE is defined as the ratio of the EMI SE to the material density, as given in Equation (9). ($dB \cdot cm^3 \cdot g^{-1}$).

$$SSE_{(foam)} = \frac{EMISE}{\rho} \tag{9}$$

To account for thickness variations in porous structures, the surface-specific shielding effectiveness parameter is used. In this case, SSE is expressed as the ratio of EMI SE to the product of density and thickness as shown in Equation (10). $(dB \cdot cm^2 \cdot g^{-1})$.

$$\frac{SSE}{t}_{(foam)} = \frac{EMISE}{\rho t} \tag{10}$$

For film-type shielding materials, density differences are usually insignificant, and the key parameter becomes the thickness (t), which indicates the EMI protection ability per unit thickness of the film. According to Equation (11), SSE is defined as $(dB \cdot mm^{-1})$:

$$SSE_{(film)} = \frac{EMISE}{t} \tag{11}$$

This expression enables fair comparison among films of varying thicknesses. Although the absorption contribution increases with thickness, SSE(film) generally saturates beyond a specific threshold thickness. Therefore, optimal design emphasizes developing configurations that achieve maximum SE at the least thickness possible.

Since weight reduction is a key design criterion in aerospace applications, the SSE(film) parameter is an excellent indicator for assessing the electromagnetic performance of CFRP layers. For example, CNT/epoxy and MXene-reinforced CFRP laminates have shown SE values of 30–50 dB and SSE(film) levels of 40–60 dB•mm^{-1} with film layers only a few hundred micrometers thick (Zhao et al., 2024; Wang et al., 2023).

Therefore, SSE(film) is considered a crucial engineering metric that enables the simultaneous optimization of high EMI shielding effectiveness and lightweight design in aerospace structural composites.

1.6.EMI Shielding Measurements

The network analyzer is one of the primary instruments used to evaluate electromagnetic interference shielding effectiveness (EMI SE). These analyzers are generally classified into two types: Scalar Network Analyzers (SNAs) and Vector Network Analyzers (VNAs). Whereas an SNA provides information solely on the amplitude of a signal, a VNA simultaneously measures both amplitude and phase. This capability enables the detailed examination of a material's electromagnetic behavior and the determination of properties such as complex permittivity (ε) and magnetic permeability (μ). As a result, the VNA is widely regarded as the instrument of choice for comprehensive EMI shielding assessments.(Cheng et al., 2022).

The VNA functions by transmitting electromagnetic waves over a specified test frequency range through two ports, while simultaneously recording the signals reflected from and transmitted through the sample being tested. These recorded responses are expressed as scattering parameters (S-parameters) and are defined as follows:

S11 is the portion of the incident wave at Port 1 that is reflected to the same port (forward reflection coefficient).

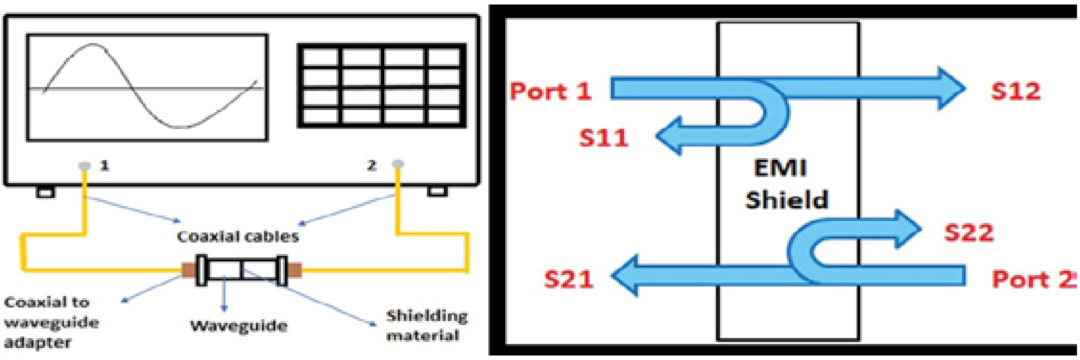
S22 is the part of the incident wave at Port 2 that is reflected to the same port (reverse reflection coefficient).

S21 is the part of the wave that enters from Port 1 and exits through Port 2 (representing the forward transmission coefficient).

S12, the part of the wave entering from Port 2 and exiting through Port 1 (backward transmission coefficient).

Figure 5

Electromagnetic Interference (EMI) Shielding Measurements Systems. a) Vector Network Analyzer, b) Scattering Parameters



The measured S-parameters allow for a quantitative description of how an electromagnetic wave interacts with a shielding material through the transmission (T), reflection (R), and absorption (A) coefficients. These coefficients are determined using the relationships presented in Equations 12–14.

$$R = |S_{11}|^2 = |S_{22}|^2 \tag{12}$$

$$T = |S_{21}|^2 = |S_{12}|^2 \tag{13}$$

$$A = 1 - R - T \tag{14}$$

The Vector Network Analyzer (VNA) allows for determining the key shielding effectiveness components—reflection loss (SER), absorption loss (SEA), and total shielding effectiveness (SET)—measured in decibels (dB) as:

$$SE_R = 10\,log\left(\frac{1}{1-|S_{11}|^2}\right) = 10\,log\left(\frac{1}{1-|S_{22}|^2}\right) = 10\,log\left(\frac{1}{1-R}\right) \tag{15}$$

$$SE_A = 10\,log\left(\frac{1-|S_{11}|^2}{|S_{12}|^2}\right) = 10\,log\left(\frac{1-|S_{22}|^2}{|S_{21}|^2}\right) = 10\,log\left(\frac{1-R}{T}\right) \tag{16}$$

$$SET = 10\,log\left(\frac{1}{|S_{12}|^2}\right) = 10\,log\left(\frac{1}{|S_{21}|^2}\right) = 10\,log\left(\frac{1}{T}\right) \tag{17}$$

Besides the SE components, the VNA results allow for the assessment of additional electromagnetic parameters, including impedance (Z), reflection loss (RL), and effective absorption (Aeff):

$$Z = Z_0\left|\frac{1+S_{11}}{1-S_{11}}\right| \tag{18}$$

$$RL = 20\,log\left(|S_{11}|\right) \tag{19}$$

$$A_{eff} = \frac{1-R-T}{1-R} \times 100\% \tag{20}$$

These relationships provide a comprehensive framework for breaking down the total shielding effectiveness into its physical components and assessing how reflection, absorption, and transmission contribute to the material's overall EMI attenuation performance (Chen et al., 2024; Kumar et al., 2018; Liang et al., 2021).

1.7.Dielectric and Magnetic Behaviour

In EMI shielding, the reflection and absorption capabilities of a material during its interaction with electromagnetic waves are primarily determined by dielectric and magnetic losses. These two mechanisms convert electromagnetic energy within the material into heat and form the basis of the absorption component (SEA). For a shielding material to be effective, both behaviours must be balanced through proper impedance matching. Excessive attenuation can cause surface impedance mismatch, leading to increased reflection, while insufficient attenuation allows wave energy to pass through without adequate dissipation within the material. Therefore, the electrical conductivity (σ), dielectric constant (ε′, ε″), magnetic permeability (μ′, μ″), and thickness (d) of the material should be optimized together. Higher electrical conductivity enhances both reflection and absorption losses, while higher magnetic permeability enhances absorption efficiency and reduces reflection. Notably, incorporating magnetic components with $\mu > 1$ into conductive composites encourages absorption-dominated shielding behaviour, supporting the development of high-performance EMI shielding materials. Consequently, precise design of the complex dielectric constant and complex magnetic permeability parameters is essential for effective electromagnetic wave absorption (Chen et al., 2024).

The dielectric behaviour of a material, determined by its permittivity (ε), describes its capacity to store electrical energy and undergo polarization when exposed to an electric field. When an electromagnetic wave creates an alternating electric field within the material, the bound charges in atoms and molecules try to reorient in response. If this reorientation cannot keep up with the oscillating field, some energy is lost as heat—a phenomenon called dielectric loss. This behaviour is mathematically expressed by the complex permittivity in Equation (21):

$$\varepsilon = \varepsilon^{'} - j\varepsilon^{''} \tag{21}$$

Where ε′ indicates the energy-storage capability, and ε″ signifies the energy dissipation or dielectric loss within the material.

The severity of loss is numerically indicated by the dielectric loss tangent (tan δ_e):

$$\tan \delta_e = \frac{\varepsilon^{''}}{\varepsilon^{'}} \tag{22}$$

A higher tan δe value indicates stronger absorption of electromagnetic energy and greater conversion into heat. However, an excessively high loss tangent can disrupt impedance matching, leading to increased surface reflections. Therefore, a balanced design of ε′ and ε″ is crucial for optimal EMI shielding performance, as demonstrated in carbon- and polymer-based composites with heterogeneous interfacial structures, enhanced interfacial polarization greatly increases dielectric losses, thereby boosting EMI attenuation efficiency (Tian et al., 2023).

Magnetic behaviour results from the interaction between the magnetic part of an electromagnetic wave and the magnetic dipoles, domain walls, and microscopic current loops inside the material. When the wave enters the medium, the alternating magnetic field causes the magnetic domains to rotate and eddy currents to form. These processes create phase delays, leading to some electromagnetic energy being turned into heat — a phenomenon called magnetic loss.

This behaviour is described by the complex magnetic permeability in Equation (23):

$$\mu = \mu^{'} - j\mu^{''} \tag{23}$$

Where μ′ indicates the material’s capacity to store magnetic energy, and μ″ represents the energy lost through magnetic dissipation.

The magnetic loss tangent quantitatively characterizes the magnitude of these losses.

$$\tan \delta_m = \frac{\mu^{''}}{\mu^{'}} \tag{24}$$

A higher tan δ_m value indicates more efficient attenuation of the magnetic component of electromagnetic waves. However, this parameter depends heavily on frequency: at low frequencies, hysteresis and domain wall motion dominate, whereas at higher frequencies, eddy currents, natural resonance, and dimensional resonance become significant. Therefore, achieving a proper balance between high μ′ (magnetic energy storage) and controlled μ″ (magnetic dissipation) is essential for maximizing absorption-dominated EMI shielding performance, especially within the X-band (8–12 GHz) range used in radar, defense, and aerospace applications (Chen et al., 2024).

Together, these dielectric and magnetic mechanisms collectively determine the absorption-dominated shielding behaviour of composite materials. Finding the right balance between electrical polarization and magnetic relaxation enables effective attenuation of incident electromagnetic energy, reducing reflection while increasing energy dissipation within the material. This combined interaction between permittivity and permeability is therefore essential for designing next-generation, lightweight, and broadband EMI shielding composites for aerospace applications.

2.EMI Shielding Effectiveness of Carbon Fiber Reinforced Polymer Composites in Aerospace Structural

Carbon fiber–reinforced polymers (CFRPs) have become essential materials in advanced engineering applications owing to their exceptional specific strength, low density, flexibility, and strong corrosion resistance. Beyond their structural merits, CFRPs are increasingly adopted as efficient EMI shielding components in aerospace systems. Integrating nanostructured fillers with high electrical conductivity or magnetic permeability—such as metallic particles, carbon nanotubes, graphene, or MXenes—can markedly improve the electromagnetic interference shielding performance of these composite materials. (Kim et al., 2023). As a result, CFRPs have become an essential material platform for next-generation aerospace systems that demand lightweight, high-performance, and electromagnetically compatible structures.

In aircraft, unidirectional CFRP laminates are commonly used in primary load-bearing elements such as wing spars and fuselage panels, where high tensile strength and low weight are essential (J. Zhang et al., 2023b). Woven and fabric-based CFRPs are preferred for secondary components such as fairings, flaps, and interior panels, offering balanced properties in multiple directions. In space applications, CFRPs are used in satellite bus structures, antenna reflectors, and payload support frames where dimensional stability and resistance to thermal cycling are critical (Ambhore, 2024). The multifunctionality of these composites, combining mechanical performance with EMI shielding, thermal management, and sensing capabilities, makes them essential materials for modern aerospace systems.

CFRPs used in aerospace structures are categorized not only by their fiber and matrix components but also by their interactions with electromagnetic waves, their shielding effectiveness, and their energy attenuation. This classification provides a crucial perspective and reference framework for understanding the application areas, performance traits, and design approaches of CFRPs in aerospace systems, especially concerning their EMI-related behaviours.

2.1.Classification According to Shielding Mechanism

The EMI shielding performance of CFRPs is primarily dictated by the dominant mechanisms that govern the interaction between the incoming electromagnetic waves and the composite material, specifically reflection, absorption, and successive internal reflections.

Reflection-dominated CFRPs exhibit high surface conductivity, leading to most incident electromagnetic energy reflecting at the air–material interface due to impedance mismatch (Jang et al., 2022; Tserpes, 2025). Conversely, absorption-dominated systems depend on dielectric and magnetic losses within the composite, converting electromagnetic energy into heat through interfacial polarization and eddy-current effects (Romero-Arismendi et al., 2024). Balanced or impedance-matched CFRPs incorporate both conductive and magnetic components, such as CNT–MXene or GR–Fe_3O_4 hybrids, to enable both reflection and absorption with minimal secondary reflections (Duan, Shi, Wang, Zhang, Zhang, et al., 2023; H. Hu et al., 2025)

In multilayered or porous structures, multiple reflection mechanisms become dominant, in which the wave undergoes successive internal scattering and attenuation at stacked conductive–dielectric interfaces (Duan, Shi, Wang, Zhang, Zhang, et al., 2023; H. Hu et al., 2025)

Table 1

Classification of CFRPs Based on EMI Shielding Mechanisms

Category	Description	Dominant Mechanism	Representative CFRP System	Specific Aerospace Application
Reflection-Dominated CFRP	High surface conductivity; most incident EM waves are reflected at the interface due to impedance mismatch.	SER > SEA	Ni- or Cu-coated CFRPs; dense CNT/graphene laminates.	Fuselage skins, radar housings, and aircraft electronic bays — where reflected EM waves must be redirected away from sensitive circuits.
Absorption-Dominated CFRP	Enhanced dielectric/ magnetic losses; EM energy converted into heat inside the composite.	SEA > SER	MXene-, Fe_3O_4-, or ferrite-modified CFRPs.	Engine nacelles, UAV signal housings, and antenna covers, where EM damping and heat dissipation are essential.
Balanced Shielding CFRP	Impedance-matched composites combining conductive and magnetic phases for dual-mode shielding.	SER ≈ SEA	CNT–MXene or CNT–graphene hybrid CFRPs.	Wing leading edges, avionics enclosures, and internal structural panels require both mechanical strength and EMI balance.

Multi-Reflection CFRP	Layered or porous structures promote internal scattering and multi-path attenuation.	High SET via SEM	CNT/BN/CNT or MXene/GR multilayer sandwiches.	Satellite payload bays, composite radomes, and instrument compartments demanding broadband shielding with low areal density.

2.2.Classification According to EMI Performance Level

The overall shielding performance of CFRPs is measured by their total shielding effectiveness (SET), which sums up the contributions from reflection (SER), absorption (SEA), and multiple reflection (SEM) mechanisms (Kim et al., 2022; Zhang & Wang, 2023). Based on their SET values and functional needs, CFRPs can be classified into different performance levels, from purely structural materials to advanced multifunctional shielding composites used in aerospace applications (Hu et al., 2025; Dong et al., 2025).

Table 2

Classification of EMI Performance Level

Category	Typical SET (dB)	Performance Level	Representative CFRP System	Specific Aerospace Application
Low-Level EMI CFRP	< 20 dB	Primarily structural; minimal EMI protection	Neat CFRP (epoxy + carbon fiber)	Wing spars, fuselage panels, and landing gear doors focus on mechanical strength and weight reduction.
Moderate-Level EMI CFRP	20–40 dB	Partial EMI shielding; enhanced electrical conductivity	CNT or graphene-filled epoxy CFRP	Aircraft interior panels, UAV fuselage sections, and radome interiors require moderate EMI suppression.

High-Level EMI CFRP	40–60 dB	Aerospace-grade composites; balanced reflection and absorption	MXene/CNT hybrid CFRPs or metal-coated fabrics	Avionics housings, engine nacelles, and electromagnetic covers protecting sensitive electronics.
Advanced EMI CFRP	> 60 dB	Superior broadband shielding; multifunctional performance	Ni-coated MXene–graphene sandwich CFRPs	Satellite payload bays, UAV antennas, radar systems, and space communication structures, where broadband attenuation and lightweight design are critical.

2.3.Classification According to Functional Composition

The EMI shielding performance of CFRPs can be tailored by introducing various functional constituents that modify their electrical, magnetic, and interfacial characteristics. Neat CFRPs, consisting only of carbon fibers and polymer matrices, provide limited shielding and serve mainly as structural materials (Vartak et al., 2022). To improve conductivity, metal-coated CFRPs are developed that incorporate metallic or magnetic layers—such as Ni–Fe or Fe_3O_4—that enhance both reflection and absorption (Shukla, 2019). Conductive polymers like PANI, PPy, and PEDOT-PSS are also used, providing lightweight, flexible pathways for charge transfer (Zheng et al., 2024). Carbon-based CFRPs containing CNTs or graphene form continuous conductive networks that enhance both reflection and internal energy dissipation (Thomassin et al., 2013; Zhong et al., 2021). MXene-based CFRPs, with their 2D metallic conductivity and adaptable surface chemistry, show excellent impedance matching and broadband electromagnetic shielding performance (Yuan et al., 2025). Lastly, hybrid CFRPs that combine conductive and magnetic phases, such as CNT–MXene or GR–Fe_3O_4, create synergistic reflection–absorption behaviour ideal for aerospace EMI applications (Irfan et al., 2023a; R et al., 2024)

2.3.1.Neat CFRPs

Neat CFRPs describe carbon fiber–reinforced polymer composites that do not incorporate additional conductive modifiers such as carbon nanotubes, MXenes, or metallic nanoparticles. Because these systems are composed solely of carbon fibers within a polymer matrix, their electrical conductivity and resulting electromagnetic interference (EMI) shielding performance remain inherently modest. For this reason, neat CFRPs are primarily valued for their mechanical advantages, including high specific strength, notable stiffness, strong fatigue resistance, and overall lightweight characteristics (J. Zhang et al., 2023a).

In aerospace and spacecraft structures, neat CFRPs are typically used in primary and secondary load-bearing parts where EMI shielding is not essential. Common examples include wing spars, fuselage skins, rib and frame components, internal structural panels, UAV fuselage beams, and satellite support trusses (J. Zhang et al., 2023a). Using them in these areas ensures optimal structural efficiency, weight savings, and mechanical reliability while keeping design simple and cost-effective compared to multifunctional or filler-modified CFRPs.

Table 3

Applications of neat CFRP in aerospace structures

Application Area	Function in Structure	Typical CFRP Configuration	Remarks
Wing spars and ribs	Primary load-bearing members transfer aerodynamic and structural loads.	Unidirectional carbon fiber/ epoxy laminates.	High stiffness and strength with low weight; limited EMI performance.
Fuselage skins and panels	Outer structural shells provide rigidity and shape retention.	Woven carbon fiber/epoxy composites.	Lightweight and corrosion-resistant; EMI shielding is not critical in these regions.
Internal structural panels	Secondary support structures for interior and control compartments.	Quasi-isotropic CFRP laminates.	Provide dimensional stability and fatigue resistance under cyclic stress.
UAV fuselage beams and frames	Lightweight structural skeleton of uncrewed aerial vehicles.	Carbon fabric-reinforced epoxy composites.	Preferred for weight reduction and mechanical integrity; low electrical conductivity.
Satellite trusses and support frames	Load-bearing and alignment components in satellite and space payload structures.	High-modulus unidirectional CFRP laminates.	Provide stiffness, thermal stability, and dimensional accuracy in vacuum environments.

2.3.2.Metal-coated CFRPs

Metal-coated CFRPs are composite materials in which the carbon fiber surface or outer layer is coated with metallic elements to improve electrical and magnetic properties. Conductive metals such as copper (Cu), nickel (Ni), silver (Ag), and aluminium (Al) are typically deposited onto the CFRP surface via electroplating, sputtering, or electroless coating to create continuous electron pathways and significantly enhance surface conductivity. Conversely, magnetic metals and alloys like cobalt (Co), iron (Fe), and nickel–iron (Ni–Fe) enhance magnetic permeability and induce eddy-current losses, thereby achieving absorption-based electromagnetic shielding. The integration of these conductive and magnetic metals enables the CFRP substrate to display dual electromagnetic responses, reflection and absorption, while preserving structural strength and lightweight qualities crucial for aerospace applications (Ouyang et al., 2025; Xie et al., 2026).

In aerospace and spacecraft structures, metal-coated CFRPs are frequently used in areas where both mechanical performance and electromagnetic compatibility are crucial. Typical applications include avionics housings, engine nacelles, radar fairings, satellite antenna supports, and electronic bay enclosures. Here, metallic coatings protect sensitive systems from external EMI and help dissipate accumulated charges. Nickel- or copper-coated CFRP laminates are especially preferred for fuselage panels and UAV body structures because they improve conductivity without adding significant weight. In high-frequency or demanding environments, Ni-Fe-coated or hybrid metallic films offer stable shielding across wide temperature ranges and radiation conditions. These multifunctional metal-coated CFRPs thus connect traditional structural composites with active electromagnetic shielding materials in next-generation aerospace systems (Pang et al., 2023; Wu et al., 2025; Yuanzhi et al., 2025)

Zhu and co-workers (2021) developed Ni-coated carbon fiber fabric/epoxy composites by applying electroless nickel plating followed by polydopamine (PDA) interfacial modification. This interface-engineered structure reached an EMI shielding effectiveness (SE) of about 31 dB, representing roughly a 77% improvement over uncoated CFRP, while also significantly improving interlaminar shear and tensile strength. Such Ni-modified CFRP systems are promising for aircraft fuselage panels, avionics housings, and access covers that require both load-bearing capacity and EMI shielding (Zhu et al., 2021).

Zhu and colleagues fabricated Ag/T-ZnO interlayered CFRP laminates by inserting silver-coated tetra-needle ZnO sheets between CF/epoxy layers through vacuum infusion. The structure achieved an EMI SE of approximately 40.99 dB (8.2–12.4 GHz), which is about 26.5 dB higher than the unmodified CFRP reference. Such Ag-interlayered CFRP skins are promising for radome-adjacent panels, avionics bay covers, and instrument fairings that need lightweight shielding (Zhu et al., 2025).

Liu and colleagues developed Ni–Fe nanoparticle-coated carbon fibers to create conductive fiber networks for EMI shielding composites. Ni and Fe nanoparticles were chemically deposited onto the carbon fiber surfaces, producing a hybrid magnetic–conductive network that simultaneously strengthened reflection and absorption losses. The engineered composite exhibited an EMI shielding effectiveness of around 52 dB within the X-band, supported by improved impedance matching and enhanced mechanical integrity. CFRP systems modified with such Ni–Fe coatings show strong potential for use in aerospace structural panels, electronic enclosure components, and UAV payload casings, where ultralight materials that integrate magnetic loss mechanisms with electrical conductivity are essential for achieving high-performance EMI shielding (Ouyang et al., 2025).

Table 4

EMI shielding performance and aerospace applications of metal-coated CFRPs

Metal Type	**Functional Role**	**Typical Coating Method**	**Aerospace Application**	**Typical EMI SE (dB)**	**Specific SE (dB•mm^{-1})**
Copper (Cu)	Provides high surface conductivity for reflection-dominated EMI shielding.	Electroplating, electroless deposition.	Avionics housings, fuselage panels, and UAV body shells for improved charge dissipation.	45–55 dB (8–18 GHz)	100–180 dB•mm^{-1}
Nickel (Ni)	Enhances both electrical conductivity and moderate magnetic loss, providing a hybrid EMI response.	Electroless plating, sputtering, or thermal spraying.	Engine nacelles, radar fairings, and satellite panels require balanced shielding and strength.	50–65 dB (0.5–18 GHz)	90–160 dB•mm^{-1}

Silver (Ag)	Exhibits excellent electrical conductivity with minimal thickness; enables high-frequency shielding.	Physical vapor deposition (PVD), sputtering.	Communication antennas, satellite enclosures, and aerospace sensors.	60–70 dB (2–26 GHz)	160–300 dB•mm^{-1}
Aluminium (Al)	A lightweight, conductive coating improves surface reflectivity while maintaining low density.	Thermal spraying or vapor deposition.	Aircraft fuselage skins and interior structural panels emphasize weight efficiency.	40–55 dB (8–12 GHz)	80–140 dB•mm^{-1}
Nickel–Iron (Ni–Fe) alloy	Provides magnetic permeability and eddy current losses for absorption-dominated shielding.	Electrochemical co-deposition or sputtering.	High-frequency shielding layers in radar systems and spacecraft components.	65–80 dB (1–18 GHz)	140–250 dB•mm^{-1}

2.3.3. Conductive Polymers

Conductive polymers (CPs) are a class of π-conjugated organic materials capable of transporting charge through delocalized π-electrons along their molecular backbone. Typical examples, such as polyaniline (PANI), polypyrrole (PPy), polythiophene (PTh), and PEDOT, exhibit electrical conductivities ranging from 10^{-4} to 10^{3} S/cm, depending on the degree of doping and structural order (Zheng et al., 2024). Their conjugated structure and mobile charge carriers enable high dielectric polarization and efficient conversion of electromagnetic energy into heat, which is the primary mechanism of absorption-dominated EMI shielding. These polymers can be processed into thin, uniform, corrosion-resistant coatings, enabling flexible and conformal EMI barriers. Recent studies have shown that PANI- and PPy-based composites can achieve 40–70 dB SE in the X-band range due to enhanced interfacial polarization and impedance matching (Turczyn et al., 2020)

In aerospace structures, conductive polymers are increasingly used as interlayers, coatings, or hybrid matrices within carbon-fiber composites to preserve electromagnetic compatibility without adding excessive weight. Their low density, chemical stability, and adjustable conductivity make them suitable for radomes, fuselage skins, and antenna housings, where metallic shields might cause galvanic corrosion or increase weight. Therefore, CP-based systems are seen as crucial components of next-generation lightweight, multifunctional aerospace composites that combine structural performance with EMI protection (Alemour et al., 2019; Das & Prusty, 2012; Yadav et al., 2020).

Table 5

EMI shielding performance and aerospace applications of Conductive Polymers

Conductive Polymer Type	Functional Role	Typical Integration Method	Aerospace Application	Typical EMI SE (dB)
Polyaniline (PANI)	Forms conductive networks and enhances interfacial polarization; absorption-dominant	In-situ polymerization on CF fabric/ epoxy matrix	Aircraft fuselage panels, avionics enclosures	≈ 54.8 dB (Kong et al., 2022)
PANI–MoS_2 hybrid	Provides multiple interfacial polarizations and dielectric loss	Surface functionalization and chemical oxidative coating	Radomes, dielectric transparent covers	≈ 41 dB (Zhou et al., 2025)
Polypyrrole (PPy)	Improves conductivity and magnetic loss balance; stable coating	In-situ chemical polymerization on the CF surface	Avionics housings, inner structural panels	≈ 74 dB (Li et al., 2024)
PANI/MXene hybrid composite	Enhanced absorption and impedance matching through conductive–dielectric coupling	Vacuum-assisted infiltration into CFRP layers	Multifunctional fuselage structures, sensor-integrated composites	≈ 62 dB (Z. Wang et al., 2021)

2.3.4. Carbon-based CFRPs

Carbon-based CFRP composites incorporate conductive nanocarbon materials mainly carbon nanotubes (CNTs) and graphene or graphene nanoplatelets (GNPs), into traditional CFRP matrices to produce lightweight, multifunctional materials with excellent EMI shielding and structural capabilities.

Carbon-based CFRPs are typically categorized into two main groups. The first includes CNT-based CFRPs, where CNTs are either grown directly on carbon fibers or added as thin interlayers (buckypaper) to enhance electrical pathways between fibers. The second comprises graphene-based CFRPs that use graphene or reduced graphene oxide (rGO) sheets as coatings or interleaved layers to enhance polarization and absorption. Both types are designed for aerospace parts such as fuselage panels, radomes, antenna housings, and avionics enclosures, where EMI shielding values of 30-70 dB are usually required (Kim et al., 2023; Suresha et al., 2025; H. Zhang et al., 2023)

In aerospace structures, carbon-based CFRPs are strategically used in fuselage skins, radomes, antenna housings, and avionics enclosures where both high EMI attenuation and weight reduction are required. Recent studies also show that these materials can effectively shield EMI while maintaining lightweight aircraft structures. (Kim et al., 2023) developed CFRP laminates reinforced with in-situ-grown CNTs, achieving an EMI shielding effectiveness (SE) of over 70 dB across the 0.3–1.5 GHz frequency range. These composites enhance charge transfer between the fibers and the matrix, making them suitable for avionics housings and internal EMI barriers. (Suresha et al., 2025) created graphene nanoplatelet (GNP) reinforced CFRP laminates with an SE of 32.4 dB in the X-band (8–12 GHz), recommending them for radome skins and electronic covers due to their corrosion resistance and light weight. Patadia et al. (2024) designed high-strength CFRP panels that achieved over 80 dB EMI SE across the X-band, demonstrating that carbon-based composites can replace metallic shields in fuselage and skin panels. Finally, (Yang et al., 2024) reviewed graphene-coated CFRP structures and highlighted their lightweight nature, corrosion resistance, and absorption-based shielding, making them ideal for radomes and antenna housings in modern aircraft.

These studies show that carbon-based CFRPs are becoming key materials for multifunctional aerospace structures, providing both mechanical performance and electromagnetic compatibility in advanced aircraft and spacecraft systems.

Table 6

EMI shielding performance and aerospace applications of Carbon-based CFRPs

CFRP Type	Representative Nanocarbon Additive	Structural Description / Integration Strategy	Aerospace Application	Typical EMI SE (dB)	Specific SE ($dB \cdot mm^{-1}$)

CNT-Modified CFRP	Multi-walled or single-walled carbon nanotubes (MWCNTs/ SWCNTs)	CNTs grafted on carbon fibers or embedded as buckypaper interlayers to create 3D conductive networks and improve through-thickness conductivity	Fuselage panels, avionics enclosures, internal EMI partitions	50–60 (Kim et al., 2023)	35–45
Graphene-Modified CFRP	Graphene nanoplatelets (GNP), reduced graphene oxide (rGO)	Graphene coatings or interleaves enhance dielectric loss and interface polarization; provide corrosion-resistant EMI shielding	Radomes, antenna housings, composite fairings	60–70 (Suresha et al., 2025)	40–55
CNT/ MXene-Reinforced CFRP	CNTs + $Ti_3C_2T_x$ MXene nanosheets	Hybrid conductive–dielectric coupling; enhanced absorption and mechanical stability	Structural EMI shielding panels, smart fuselage composites	65–75 (J. Dong et al., 2025)	50–60

2.3.5.MXene-based CFRPs

MXene-based CFRP composites are a new type of lightweight, multifunctional materials that incorporate two-dimensional $Ti_3C_2T_x$ MXene nanosheets into carbon fiber/epoxy systems. This integration can be achieved through surface coating of carbon fabrics, insertion of MXene interleaves, or direct functionalization of the fiber surface. The resulting structures demonstrate high electrical conductivity, broad-band absorption, and excellent interfacial compatibility, making them promising options for next-generation EMI shielding in aerospace applications (Liu et al., 2023; Q. Zhang et al., 2023)

Several recent studies have examined the direct integration of MXenes into CFRP systems, reporting significant improvements in electromagnetic shielding performance. Yilmaz et al. (2025) produced MXene-sprayed carbon fabric/epoxy CFRP laminates using vacuum infusion. They achieved an overall EMI SE of approximately 32 dB in the X-band, along with improved interlaminar shear and flexural strength—demonstrating a scalable fabrication method for multifunctional CFRP structures. According to Zhang et al. (2024), coated CF/PEEK thermoplastic CFRP tapes with $Ti_3C_2T_x$ MXene to enhance interfacial bonding, reporting a specific EMI SE of about 80.8 dB•mm^{-1} and framing their work within a clear aerospace context (Zhang et al., 2024). Similarly, Irfan et al. (2023b) fabricated MXene-coated aerospace-grade fiber composites with dual EMI shielding and sensing capabilities, noting superior attenuation compared to rGO-coated counterparts. Finally, Duan et al. (2023) developed a $Ti_3C_2T_x$-MXene/graphene oxide interleaved carbon-fabric composite that achieved approximately 38 dB SE in the X-band, providing a design model easily adaptable to CFRP laminates for aerospace applications.

Table 7

EMI shielding performance and aerospace applications of MXene-based CFRPs

Composite System	EMI SE (dB)	Main Features and Findings	Application / Remarks
$Ti_3C_2T_x$ MXene / GO/carbon fabric multilayer	38 dB	Flexible multilayer architecture; absorption-dominant shielding; stable under bending.	Scalable thin shielding films for aerospace panels. (Duan et al., 2023)
Recycled carbon fiber (MXene-coated) sandwich paper	45.7 dB	Lightweight, recyclable, and highly conductive; high specific SE per thickness.	Potential EMI shields for aircraft interiors and UAV bodies. (Liu et al., 2022)
MXene-sprayed carbon fabric/epoxy laminate	32.8 dB	Improved fiber–matrix adhesion and conductivity; strong laminate.	Structural EMI shielding for aerospace components. (Yilmaz et al., 2025)
$Ti_3C_2T_x$ MXene-coated CF/PEEK thermoplastic tapes	80.8 dB•mm^{-1} (specific SE)	Strengthened interfacial bonding; very high specific EMI SE; thermoplastic processing suitable for aircraft.	Explicitly aerospace-oriented CFRP design with dual mechanical-EMI functionality. (Zhang et al., 2024)

Although MXene-CFRPs have proven to be excellent EMI shielding materials, their direct application in real aerospace structures remains limited. Most work still occurs at the laboratory or prototype level. However, future opportunities are clear: MXene-based CFRPs are ideal for radomes, antenna housings, avionics enclosures, fuselage skins, and satellite fairing panels, where low weight and effective EMI absorption are essential. As surface engineering and oxidation-stability challenges are addressed, these multifunctional composites are expected to play a significant role in next-generation lightweight aerospace systems (Iqbal et al., 2020; Lang et al., 2024).

2.3.6.Hybrid CFRPs

Hybrid CFRP composites are advanced multifunctional systems in which two or more types of conductive or magnetic nanomaterials are embedded in the CFRP matrix or layered structure to create synergistic effects. In these hybrids, the traditional carbon fiber/epoxy or CF/PEEK framework is combined with various functional nanofillers, such as CNT + graphene, MXene + metal nanoparticles (Ag, Ni, Fe_3O_4), or conductive polymer + carbon-based nanofillers. These multiscale designs leverage the complementary mechanisms of conduction and polarization loss to enhance impedance matching and enable broadband, absorption-dominant EMI shielding. The resulting hybrid CFRPs offer mechanical strength, thermal stability, and electrical conductivity, which are highly valued for aerospace fuselage panels, antenna radomes, and avionics housings where lightweight multifunctionality is essential (Anggereni & Tahir, 2025; Gao et al., 2023).

Recent Scopus-indexed studies confirm the excellent EMI shielding capabilities of hybrid CFRPs. Zhang et al. (2024b) fabricated a graphene/MXene-coated CF/epoxy laminate, achieving a total EMI SE of around 68 dB in the X-band through combined absorption and reflection; the authors proposed its use for aircraft skin structures. Liu et al. (2023) developed a Ni-CNT hybrid network integrated into CFRP laminates, reaching approximately 72 dB shielding while maintaining mechanical integrity, demonstrating its suitability for aerospace electronic housings. (Yilmaz et al., 2025) reported a MXene/graphene oxide-modified carbon-fabric/epoxy composite with an EMI SE over 60 dB and enhanced conductivity, recommending it for fuselage and radome shells. Similarly, Wang et al. (2022) achieved an impressive 80 dB EMI SE in CNT/Fe_3O_4-decorated CFRP, highlighting magnetic–conductive hybrid coupling as an effective means to enhance attenuation.

Table 8

EMI shielding performance and aerospace applications of Hybrid CFRPs

Hybrid System	Matrix / Substrate	EMI SE (dB)	Dominant Mechanism	Suggested Aerospace Application

Graphene / MXene hybrid coating	CF/Epoxy laminate	68 dB (X-band)	Synergistic absorption + reflection	Suitable for aircraft skin panels and outer fuselage shells, providing high absorption and structural compatibility.(Hu et al., 2024)
Ni-CNT hybrid network	CF/Epoxy composite	72 dB (X-band)	Conductive + magnetic loss coupling	Effective for avionics housings and electronic bays, offering strong EMI attenuation with minimal mass increase. (Liu et al., 2023)
MXene / Graphene-oxide modified carbon fabric	CF/Epoxy laminate	> 60 dB (X-band)	Interfacial polarization + absorption	Applicable to radome and fuselage panels, ensuring broadband EMI absorption and improved interfacial conductivity. (Patadia et al., 2024)
CNT / Fe_3O_4 decorated carbon fiber fabric	CF/Epoxy laminate	80 dB (X-band)	Magnetic–conductive hybrid coupling	Designed for antenna fairings and electronic enclosures, achieving ultrahigh EMI SE through magnetic–conductive synergy. (Wang et al., 2022)

Overall, these results demonstrate that hybrid nanostructures effectively achieve EMI shielding above 60 dB while maintaining the lightweight and structural benefits of traditional CFRPs. This makes them important materials for future aerospace applications.

Conclusion and Future Perspectives

Carbon fiber reinforced polymer (CFRP) composites remain essential materials for aerospace structures, valued for their high specific strength, stiffness, and lightweight nature. As electronic density in aircraft, satellites, and UAV platforms continues to increase, the need for structural components that also provide reliable electromagnetic interference (EMI) shielding has become critical. While neat CFRPs offer moderate shielding from their intrinsic conductivity, they are insufficient for protecting sensitive systems such as radar modules, navigation electronics, and high-frequency communication units.

Recent research demonstrates that modifying CFRPs with conductive or magnetic nanomaterials—such as MXenes, CNTs, graphene, or metal coatings—can achieve shielding effectiveness levels of 50–80 dB in the X-band without sacrificing mechanical performance. These enhanced composites show strong potential for integration into fuselage skin panels, radomes, antenna fairings, avionics bay covers, payload housings on UAVs, and satellite instrument enclosures, where lightweight EMI protection and structural reliability must be combined.

Despite these advancements, challenges remain regarding scalable manufacturing, environmental durability, and the lack of standardized testing protocols tailored to aerospace conditions. Future research should emphasize large-scale process optimization, hybrid filler architectures, and comprehensive evaluation under aerospace-specific thermal, mechanical, and vibration loads. With such developments, hybrid-modified CFRPs are positioned to evolve into true multifunctional materials capable of simultaneously carrying structural loads and ensuring robust EMI protection across next-generation aerospace platforms.

References

Alemour, B., Badran, O., & Hassan, M. R. (2019). A review of using conductive composite materials in solving lightening strike and ice accumulation problems in aviation. *Journal of Aerospace Technology and Management*, *11*, 1–23. https://doi.org/10.5028/jatm.v11.1022

Ambhore, N. (2024). *Carbon Composites in Aerospace Application -A Comprehensive Review Carbon Composites in Aerospace Application - A Comprehensive Review*. *March*. https://doi.org/10.33263/Materials54.002

Anggereni, S., & Tahir, P. L. G. D. (2025). Sandwich composite structures for electromagnetic pollution shielding : materials , mechanical performance , and shielding effectiveness. *International Journal of Environmental Science and Technology*, *22*(16), 17465–17488. https://doi.org/10.1007/s13762-025-06699-5

Chen, G., Li, Z., Zhang, L., Chang, Q., Chen, X., & Fan, X. (2024). Review Mechanisms , design , and fabrication strategies for emerging electromagnetic wave-absorbing materials. *Cell Reports Physical Science*, *5*(7), 102097. https://doi.org/10.1016/j.xcrp.2024.102097

Cheng, J., Li, C., Xiong, Y., Zhang, H., Raza, H., Ullah, S., Wu, J., Zheng, G., Cao, Q., Zhang, D., Zheng, Q., & Che, R. (2022). Recent Advances in Design Strategies and Multifunctionality of Flexible Electromagnetic Interference Shielding Materials. In *Nano-Micro Letters* (Vol. 14, Issue 1). Springer Nature Singapore. https://doi.org/10.1007/s40820-022-00823-7

Das, T. K., & Prusty, S. (2012). Review on Conducting Polymers and Their Applications. *Polymer - Plastics Technology and Engineering*, *51*(14), 1487–1500. https://doi.org/10.1080/03602559.2012.710697

Dong, J., Liu, C., Cheng, H., Jiang, C., Zhou, B., Huang, M., Liu, C., & Feng, Y. (2025). Recent progress of Ti3C2Tx MXene-based layered films for electromagnetic interference shielding. *Journal of Materials Science and Technology*, *223*, 131–149. https://doi.org/10.1016/j.jmst.2024.10.032

Dong, W., Karalis, G., Liebscher, M., Wang, T., Liu, P., Li, W., & Mechtcherine, V.

(2025). Multifunctional carbon fibre reinforced polymer (CFRP) composites for sustainable and smart civil infrastructure: A comprehensive review. *Sustainable Materials and Technologies*, *45*(August), e01594. https://doi.org/10.1016/j.susmat.2025.e01594

Duan, N., Shi, Z., Wang, J., Zhang, C., Xi, J., Yang, X., & Wang, G. (2023). Multilayer Ti3C2Tx MXene/graphene oxide/carbon fiber fabric/thermoplastic polyurethane composite for improved mechanical and electromagnetic interference shielding performance. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *677*(PA), 132339. https://doi.org/10.1016/j.colsurfa.2023.132339

Duan, N., Shi, Z., Wang, J., Zhang, X., Zhang, C., Zhang, C., & Wang, G. (2023). Multilayer-structured carbon fiber fabric/graphene oxide/Fe3O4/epoxy composite for highly efficient mechanical and electromagnetic interference shielding. *Applied Surface Science*, *613*(November 2022), 156038. https://doi.org/10.1016/j.apsusc.2022.156038

Dungani Rudi, P. A. A. S., Yuniarti Karnita, Karliati Tati, S. I. and, & Ihak, S. (2018). We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %. *Long-Haul Travel Motivation by International Tourist to Penang*, *i*(tourism), 13.

Gao, R. X., Member, S., Lee, H. M., Ewe, W. Bin, Member, S., Tay, S. W., Thitsartarn, W., & Yang, Z. (2023). Electromagnetic Characterization and Measurement of Conductive Aircraft CFRP Composite for Lightning Protection and EMI Shielding. *IEEE Transactions on Instrumentation and Measurement*, *72*, 1–11. https://doi.org/10.1109/TIM.2023.3325509

Hamzat, A. K., Murad, M. S., Adediran, I. A., Asmatulu, E., & Asmatulu, R. (2025). Fiber-reinforced composites for aerospace, energy, and marine applications: an insight into failure mechanisms under chemical, thermal, oxidative, and mechanical load conditions. In *Advanced Composites and Hybrid Materials* (Vol. 8, Issue 1). https://doi.org/10.1007/s42114-024-01192-y

Hirankittiwong, P., Chomchok, T., Chakraborty, S., Prajongtat, P., Singh, D. P., Hongkarnjanakul, N., Channumsin, S., Ghosh, S., & Chattham, N. (2025). Advanced engineered nanostructures for aerospace technology: A review. *Results in Engineering*, *26*(May). https://doi.org/10.1016/j.rineng.2025.105381

Hlo, K. (2021). *Nanoscale Advances Progress in polymers and polymer composites used as e ffi cient materials for EMI shielding*. 123–172. https://doi.org/10.1039/d0na00760a

Hu, H., Wang, S., Zhang, Y., Wang, X., Lin, B., Zhang, S., Zhang, W., & Lian, P. (2025). MXene-Based Electromagnetic Interference Shielding Materials: A Leap From Fundamental Research to Intelligent Customization. *Small*, *2505417*, 1–42. https://doi.org/10.1002/smll.202505417

Hu, Y., Yang, G., Chen, J., Li, Y., Dong, M., & Zhang, H. (2024). *Interfacial engineering of hybrid MXene-Ni-CF tri-core – shell composites for electromagnetic interference shielding and E-heating applications*. *178*(December 2023). https://

doi.org/10.1016/j.compositesa.2023.107990

Iqbal, A., Sambyal, P., & Koo, C. M. (2020). *2D MXenes for Electromagnetic Shielding : A Review*. *2000883*, 1–25. https://doi.org/10.1002/adfm.202000883

Irfan, M. S., Ali, M. A., Khan, T., Anwer, S., Liao, K., & Umer, R. (2023a). MXene and graphene coated multifunctional fiber reinforced aerospace composites with sensing and EMI shielding abilities. *Composites Part A: Applied Science and Manufacturing*, *165*(November 2022), 107351. https://doi.org/10.1016/j.compositesa.2022.107351

Irfan, M. S., Ali, M. A., Khan, T., Anwer, S., Liao, K., & Umer, R. (2023b). MXene and graphene coated multifunctional fiber reinforced aerospace composites with sensing and EMI shielding abilities. *Composites Part A: Applied Science and Manufacturing*, *165*(June 2022), 107351. https://doi.org/10.1016/j.compositesa.2022.107351

Ismail, I., & Azis, S. (2024). Review A review of magnetic nanocomposites for EMI shielding : synthesis , properties , and mechanisms. In *Journal of Materials Science* (Vol. 59, Issue 13). Springer US. https://doi.org/10.1007/s10853-024-09527-2

Jang, D., Kim, B. J., & Nam, I. W. (2022). A Comprehensive Study on EMI Shielding Performance of Carbon Nanomaterials-Embedded CFRP or GFRP Composites. *Polymers*, *14*(23), 1–12. https://doi.org/10.3390/polym14235224

Kim, D., Han, W., Kim, K., & Kim, B. (2023). *Electromagnetic Interference Shielding Effectiveness of Direct-Grown-Carbon Nanotubes / Carbon and Glass*.

Kong, W., Yi, S., Sun, W., Xu, L., Jia, L., Yan, D., & Li, Z. (2022). Polyaniline-decorated carbon fibers for enhanced mechanical and electromagnetic interference shielding performances of epoxy composites. *Materials and Design*, *217*, 110658. https://doi.org/10.1016/j.matdes.2022.110658

Kruželák, J., Kvasničáková, A., Hložeková, K., & Hudec, I. (2021). Progress in polymers and polymer composites used as efficient materials for EMI shielding. *Nanoscale Advances*, *3*(1), 123–172. https://doi.org/10.1039/d0na00760a

Kumar, A., Shishkin, A., Koppel, T., & Gupta, N. (2018). A review of porous lightweight composite materials for electromagnetic interference shielding. *Composites Part B*, *149*(March), 188–197. https://doi.org/10.1016/j.compositesb.2018.05.027

Lang, L., Zou, Y., Yan, X., Zhu, J., & Liu, Y. (2024). *A review of recent advances in MXenes / polymer-based electromagnetic interference shielding materials*. *April*, 11541–11559. https://doi.org/10.1002/pc.28627

Li, H., Li, J., Chu, W., Lin, J., Xin, J., Liu, F., Li, Z., & Ma, Z. (2024). Flexible Hierarchical Polyimide/Polypyrrole/Carbon Nanofiber Composite Films for Tunable Electromagnetic Interference Shielding. *ACS Applied Nano Materials*, *7*(7), 7783–7793. https://doi.org/10.1021/acsanm.4c00415

Liang, C., Gu, Z., Zhang, Y., Ma, Z., Qiu, H., & Gu, J. (2021). Structural Design Strategies of Polymer Matrix Composites for Electromagnetic Interference Shielding : A Review. *Nano-Micro Letters*, *13*(1), 1–29. https://doi.org/10.1007/s40820-021-00707-2

Liu, Y., Wang, Y., Wu, N., Han, M., Liu, W., Liu, J., & Zeng, Z. (2023). Diverse Structural Design Strategies of MXene-Based Macrostructure for High-Performance Electromagnetic Interference Shielding. *Nano-Micro Letters*, *15*(1). https://doi.org/10.1007/s40820-023-01203-5

Liu, Y., Wu, N., Zheng, S., Yang, Y., Li, B., Liu, W., Liu, J., & Zeng, Z. (2022). *From MXene Trash to Ultraflexible Composites for Multifunctional Electromagnetic Interference Shielding*. https://doi.org/10.1021/acsami.2c13849

Manjunath, V. M. G., & Virupaxi, V. (2025). *A Review on Conductive Polymer Composites Focusing on Advancements in Electrical Conductivity , and Electromagnetic Shielding Capabilities*. 1–31. https://doi.org/10.1002/pc.70059

Maria, M. (2013). Advanced composite materials of the future in aerospace industry. *Incas Bulletin*, *5*(3), 139–150. https://doi.org/10.13111/2066-8201.2013.5.3.14

Mishra, R. K., Thomas, M. G., Abraham, J., Joseph, K., & Thomas, S. (2018). Electromagnetic Interference Shielding Materials for Aerospace Application. *Advanced Materials for Electromagnetic Shielding*, *August*, 327–365. https://doi.org/10.1002/9781119128625.ch15

Ouyang, X., Duan, S., Ji, J., Liu, Y., Tian, W., Niu, K., & Wei, Y. (2025). Study on the Compressive Strength of Carbon Fiber Reinforced Polymer Composites – A Lesson Learned from Composite Structure Design for Large Commercial Aircraft. *Advanced Materials Technologies*, *10*(18), 1–14. https://doi.org/10.1002/admt.202500549

Pang, J., Qin, W., You, W., Zhong, M., & Meng, Q. (2023). Induction Heating Characteristics of Electroless Ni-Coated CFRP for Deicing and Anti-Icing. *Coatings*, *13*(9). https://doi.org/10.3390/coatings13091531

Parveez, B., Kittur, M. I., Badruddin, I. A., Kamangar, S., Hussien, M., & Umarfarooq, M. A. (2022). Scientific Advancements in Composite Materials for Aircraft Applications: A Review. *Polymers*, *14*(22). https://doi.org/10.3390/polym14225007

Parvez, M. A., Islam, M., Sultana, S., & Ali, M. (2025). Recent development on polymer based light weight electromagnetic interference shielding materials. In *Journal of Materials Science: Materials in Electronics* (Vol. 36, Issue 14). Springer US. https://doi.org/10.1007/s10854-025-14836-6

Prekodravac Filipovic, J., Milenkovic, M., Kepic, D., Dorontic, S., Yasir, M., Nardin, B., & Jovanovic, S. (2025). Electromagnetic Interference in the Modern Era: Concerns, Trends, and Nanomaterial-Based Solutions. *Nanomaterials*, *15*(20), 1–34. https://doi.org/10.3390/nano15201558

R, S., Shivamurthy, B., H. K, S., Prabhu, N. N., Prabhu, P. M., & Selvam, R. (2024). CFRP hybrid composites manufacturing and electromagnetic wave shielding performance-a review. *Cogent Engineering*, *11*(1), 1–19. https://doi.org/10.1080/23311916.2024.2306556

Romero-Arismendi, N. O., Olivares-Galvan, J. C., Hernandez-Avila, J. L., Escarela-Perez, R., Jimenez-Mondragon, V. M., & Gonzalez-Montañez, F. (2024). Past, Present, and Future of New Applications in Utilization of Eddy Currents. *Technologies*, *12*(4). https://doi.org/10.3390/technologies12040050

Rouhi, M., Hajizadeh, Z., Taheri-Ledari, R., Maleki, A., & Babamoradi, M. (2022). A review of mechanistic principles of microwave absorption by pure and composite nanomaterials. *Materials Science and Engineering: B*, *286*(February), 116021. https://doi.org/10.1016/j.mseb.2022.116021

ScienceNotes.org. (n.d.). Electromagnetic spectrum: Definition and explanation. https://sciencenotes.org/electromagnetic-spectrum-definition-and-explanation/

Shukla, V. (2019). Review of electromagnetic interference shielding materials fabricated by iron ingredients. *Nanoscale Advances*, *1*(5), 1640–1671. https://doi.org/10.1039/c9na00108e

Siengchin, S. (2023). A review on lightweight materials for defence applications: Present and future developments. *Defence Technology*, *24*, 1–17. https://doi.org/10.1016/J.DT.2023.02.025

Suresha, R., Sachidananda, H. K., Shivamurthy, B., Swamy, N. K., & Parasuram, S. (2025). Mechanical and electromagnetic shielding properties of carbon fabric with graphene nanoplatelets reinforced epoxy composites. *Scientific Reports*, *15*(1), 1–14. https://doi.org/10.1038/s41598-025-00634-x

Thomassin, J. M., Jérôme, C., Pardoen, T., Bailly, C., Huynen, I., & Detrembleur, C. (2013). Polymer/carbon based composites as electromagnetic interference (EMI) shielding materials. *Materials Science and Engineering R: Reports*, *74*(7), 211–232. https://doi.org/10.1016/j.mser.2013.06.001

Tian, K., Hu, D., Wei, Q., Fu, Q., & Deng, H. (2023). Journal of Materials Science & Technology Recent progress on multifunctional electromagnetic interference shielding polymer composites. *Journal of Materials Science & Technology*, *134*, 106–131. https://doi.org/10.1016/j.jmst.2022.06.031

Tserpes, K. (2025). *Advances in Composite Materials for Space Applications : A Comprehensive Literature Review*.

Turczyn, R., Krukiewicz, K., Katunin, A., Sroka, J., & Sul, P. (2020). Fabrication and application of electrically conducting composites for electromagnetic interference shielding of remotely piloted aircraft systems. *Composite Structures*, *232*(September 2019). https://doi.org/10.1016/j.compstruct.2019.111498

Vartak, D. A., Satyanarayana, B., Munjal, B. S., Vyas, K. B., Bhatt, P., & Lal, A. K. (2022). Potential applications of advanced nano-composite materials for space payload. *Australian Journal of Mechanical Engineering*, *20*(3), 651–659. https://doi.org/10.1080/14484846.2020.1733176

Wang, X. Y., Liao, S. Y., Wan, Y. J., Zhu, P. L., Hu, Y. G., Zhao, T., Sun, R., & Wong, C. P. (2022). Electromagnetic interference shielding materials: recent progress, structure design, and future perspective. *Journal of Materials Chemistry C*, *10*(1), 44–72. https://doi.org/10.1039/d1tc04702g

Wang, Z., Cheng, Z., Xie, L., Hou, X., & Fang, C. (2021). Flexible and lightweight Ti3C2Tx MXene/Fe3O4@PANI composite films for high-performance electromagnetic interference shielding. *Ceramics International*, *47*(4), 5747–5757. https://doi.org/10.1016/j.ceramint.2020.10.161

Wdowiak, A., Mazurek, P. A., Wdowiak, A., & Bojar, I. (2017). Effect of electromagnetic waves on human reproduction. *Annals of Agricultural and Environmental Medicine*, *24*(1), 13–18. https://doi.org/10.5604/12321966.1228394

Wu, J., Gao, Y., Lu, Z., Yang, X., & Xin, B. (2025). Electromagnetic shielding performance of copper wire/carbon fiber fabric reinforced composite materials. *Journal of Reinforced Plastics and Composites*, *44*(13–14), 809–817. https://doi.org/10.1177/07316844241230732

Xia, Q. (2023). Overview of aerospace materials and their applications. *Theoretical and Natural Science*, *13*(1), 115–120. https://doi.org/10.54254/2753-8818/13/20240808

Xie, M., Zhan, L., Ma, B., Cao, Z., & Yu, R. (2026). Improved interfacial and electrochemical properties of CFRP via nano-Fe2O3 coated carbon fibers. *Materials Letters*, *404*(July 2025), 139557. https://doi.org/10.1016/j.matlet.2025.139557

Yadav, R., Tirumali, M., Wang, X., Naebe, M., & Kandasubramanian, B. (2020). Polymer composite for antistatic application in aerospace. *Defence Technology*, *16*(1), 107–118. https://doi.org/10.1016/j.dt.2019.04.008

Yang, S. J., Cao, Y., He, Y. B., & Lv, W. (2024). A review of the use of graphene-based materials in electromagnetic-shielding. *Xinxing Tan Cailiao/New Carbon Materials*, *39*(2), 223–239. https://doi.org/10.1016/S1872-5805(24)60840-1

Yao, Y., Jin, S., Zou, H., Li, L., Ma, X., & Lv, G. (2021). Polymer-based lightweight materials for electromagnetic interference shielding : a review. *Journal of Materials Science*, *56*(11), 6549–6580. https://doi.org/10.1007/s10853-020-05635-x

Yuan, X., Li, S., Qin, R., Zhang, M., Zhu, B., & Cao, W. (2025). Advances in constructing Carbon Fiber-MXene multilevel structures to reinforce interfacial properties of carbon fiber reinforced polymer composites. *Polymer Composites*, *46*(6), 5041–5063. https://doi.org/10.1002/pc.29314

Yuanzhi, L., Siguang, Y., Yingming, S., Sijie, B., Ziang, G., Chaoyi, W., & Wenzhuang, L. (2025). Ultra-broadband electromagnetic shielding properties of Cu/Ni coatings on CFRP. *Materials Science and Engineering: B*, *322*(July), 118539. https://doi.org/10.1016/j.mseb.2025.118539

Yuksel Yilmaz, A. N., Bedeloglu, A. C., & Yunus, D. E. (2025). The effect of MXene on the mechanical and electromagnetic interference shielding features of carbon fabric/epoxy scalable laminated composites. *Journal of Materials Science*, *60*(19), 7965–7983. https://doi.org/10.1007/s10853-025-10924-4

Zhang, H., Zheng, X., Jiang, R., Liu, Z., Li, W., & Zhou, X. (2023). Research progress of functional composite electromagnetic shielding materials. *European Polymer Journal*, *185*(January), 111825. https://doi.org/10.1016/j.eurpolymj.2023.111825

Zhang, J., Lin, G., Vaidya, U., & Wang, H. (2023a). Past, present and future prospective of global carbon fibre composite developments and applications. *Composites Part B: Engineering*, *250*(July 2022), 110463. https://doi.org/10.1016/j.compositesb.2022.110463

Zhang, J., Lin, G., Vaidya, U., & Wang, H. (2023b). Past , present and future prospective of global carbon fibre composite developments and applications. *Composites Part B*, *250*(July 2022), 110463. https://doi.org/10.1016/j.compositesb.2022.110463

Zhang, Q., Wang, Q., Cui, J., Zhao, S., Zhang, G., Gao, A., & Yan, Y. (2023). Structural design and preparation of Ti3C2Tx MXene/polymer composites for absorption-dominated electromagnetic interference shielding. *Nanoscale Advances*, *5*(14), 3549–3574. https://doi.org/10.1039/d3na00130j

Zhang, S., Cui, J., Kuang, X., Lai, M., Luo, Y., Bao, F., Yu, J., Zhu, C., Xu, J., & Liu, H. (2024a). Simultaneously enhancing the EMI shielding performances and mechanical properties of structure–function integrated CF/PEEK composites via chopped ultra-thin carbon fiber tapes and interfacial engineering with MXene. *Chemical Engineering Journal*, *500*(October), 156823. https://doi.org/10.1016/j.cej.2024.156823

Zhang, S., Cui, J., Kuang, X., Lai, M., Luo, Y., Bao, F., Yu, J., Zhu, C., Xu, J., & Liu, H. (2024b). Simultaneously enhancing the EMI shielding performances and mechanical properties of structure – function integrated CF / PEEK composites via chopped ultra-thin carbon fiber tapes and interfacial engineering with MXene. *Chemical Engineering Journal*, *500*(October), 156823. https://doi.org/10.1016/j.cej.2024.156823

Zheng, S., Wang, Y., Wang, X., & Lu, H. (2024). Research progress on high-performance electromagnetic interference shielding materials with well-organized multilayered structures. *Materials Today Physics*, *40*(December 2023), 101330. https://doi.org/10.1016/j.mtphys.2024.101330

Zheng, S., Wang, Y., Zhu, Y., & Zheng, C. (2024). Recent advances in structural design of conductive polymer composites for electromagnetic interference shielding. *Polymer Composites*, *45*(1), 43–76. https://doi.org/10.1002/pc.27773

Zhong, L., Yu, R., & Hong, X. (2021). Review of carbon-based electromagnetic shielding materials: film, composite, foam, textile. *Textile Research Journal*, *91*(9–10), 1167–1183. https://doi.org/10.1177/0040517520968282

Zhou, J., Song, Z., Wan, J., Zhou, M., Zhu, B., Qiao, K., & Cai, X. (2025). Polyaniline-functionalized MoS2 nanosheets/carbon fiber network for structural and functional integration of composites. *Composites Part B: Engineering*, *306*(July), 112847. https://doi.org/10.1016/j.compositesb.2025.112847

Zhu, S., Shi, R., Qu, M., Zhou, J., Ye, C., Zhang, L., Cao, H., Ge, D., & Chen, Q. (2021). Simultaneously improved mechanical and electromagnetic interference shielding properties of carbon fiber fabrics/epoxy composites via interface engineering. *Composites Science and Technology*, *207*(July 2020), 108696. https://doi.org/10.1016/j.compscitech.2021.108696

About The Authors

Osman Fatih DAMNALI is a Doctor of Mechanical Engineering at Technical Science Vocational School, Çanakkale Onsekiz Mart University in Çanakkale, Türkiye. He is a Dr. Lecturer in the Department of Machine and Metal Technologies at Çanakkale Onsekiz Mart University. His main areas of interest are Composite Materials, Nano Materials, and Cellulose.

E-mail: fatihdamnali@comu.edu.tr, **ORCID:** 0000-0002-6678-6099

Volkan ESKİZEYBEK is an Associate Professor of Mechanical Engineering at Engineering Faculty, Çanakkale Onsekiz Mart University in Çanakkale, Türkiye. His main areas of interest are Composites, Nanomaterials, Mechanical Properties, Material Characterization, Semiconductor, and Superconductor Materials.

E-mail: veskizeybek@comu.edu.tr, **ORCID:** 0000-0002-5373-0379

Hüseyin ARIKAN is a Professor of Mechanical Engineering at Seydişehir Ahmet Cengiz Engineering Faculty, Necmettin Erbakan University in Konya, Turkey. His main areas of interest are Composite Materials, Fracture Mechanics, and Materials Design and Manufacturing.

E-mail: harikan@erbakan.edu.tr, **ORCID:** 0000-0003-1266-4982

Similarity Index:

The similarity index obtained from the plagiarism software for this book chapter is 14%.