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DEVELOPMENT OF ADVANCED MICROWAVE ABSORBING MATERIALS FOR ELECTROMAGNETIC INTERFERENCE (EMI) SHIELDING IN NEXT-GENERATION ELECTRONIC SYSTEMS

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Article Info

Abstract
The growing use of portable electronic equipment and wireless communication systems has amplified the issue of electromagnetic interference (EMI), thus the need to design high-performance microwave absorbing materials. That is why traditional metal based shielding materials are good conductors but they include high density, corrosion and poor fatigue resistance and are rigid in nature. This work investigates the fabrication and EMI shielding characteristics of graphene, CNTs, MXenes, and the polymer-ferrite composites based on electrical conductivity, dielectric constant, mechanical strength, and thermal stability. In the case of shielding effectiveness, the MXene composites afforded 52.4 dB which is much higher than for graphene (42.1 dB) and CNT-polymer composites (39.2 dB) because of its higher conductivity and efficient absorption properties. In comparison to the commercial shielding materials, it was realized that these composites provided propitious performance enhancement in flexibility and considerably low weight. The results indicate that coating with MXene can integrate excellent properties with polymers to be the most potential candidates for the next-generation EMI shielding applications especially for 5G, IoT, aerospace, and wearable electronics. Additional research directions include improving large scale fabrication technology, combining carbon nanostructures, and discovering environmentally friendly shielding materials.

Keywords:
Electromagnetic interference (EMI), microwave-absorbing materials, MXenes, graphene, carbon nanotubes (CNTs), polymer composites, shielding effectiveness, next-generation electronics.

Introduction

Electromagnetic interference is essential in present-day integrated electronic systems because of the enhancement in packing density of the components and the complexity of wireless communications systems. The increasing density of the EM waves, produced by handheld devices, radars, satellite devices, and self-driving cars has led to concerns on signal quality, system reliability, and effects on human body (Wang et al., 2021). As such due to continuous evolution in 5G, IoTs, and AI-related technologies, effective EMI shielding materials to counter electromagnetic pollution are critically desired (Li et al., 2020).

Interference, abbreviated as EMI, refers to the degree of disruption brought about by power carried in the form of electromagnetic radiation which interrupts the proper functioning of the electrical circuits. It is classified as natural interference that comes from lightning and sunspot and interference from artificial sources, for instance, power lines, circuits, and Wireless communications devices (Saini et al., 2021). The effects of EMI are mainly the degradation of signals, failure of crucial medical instruments, inconvenience in radar systems, and security risks in defense industries (Liu et al., 2020). Incorporation of nanoelectronics in Biomedical devices along with Aerospace applications has made EMI shielding an essential area of investigation in material science.

Copper, aluminum and silver have been widely used as traditional EMI shielding materials because they possess good electrical conductivity and high shielding efficacy (Cheng et al., 2021). But metallic shields have some demerits that include the following: high density, property vulnerability, low flexibility, and expensive manufacturing costs (as stated by Huang et al., 2020). Also, to address the need for low weight, flexibility and transparency in wearable devices, flexible circuits, and transparent EMI shielding, conventional metallic materials (Kim et al., 2021).

To address such limitations, scholars have focused on the development of novel microwave-absorbing materials with higher EMI shielding effectiveness, lightweight, flexibility, and durability (Zhang et al., 2022). Out of these materials, nanocarbons, for instance, graphene, CNTs and MXenes have captured significant prospects of microwave absorption as a result of their high conductivity, switchable dielectrics, besides their nanoarchitecture (Zou et al., 2021). Additionally, ferrites and other transition metal oxides have been added to polymers for boosting magnetic loss mechanisms mainly to better the overall absorption efficacy (Chen et al., 2020).

The modern developments have been more inclined towards polymer based composites where conductive phases like graphene, CNTs and MXenes transfer in polymer back bone to obtain EMI shielding property (Jiang et al., 2021). PANI, PPy, and epoxy resins offer the necessary material flexibility, chemical stability, and processability together with a satisfactory EMI shielding performance (Zhao, Liang, Hou, Zhang, & Chen, 2021). The use of MWNTs in polymer based composites leads to an increase in the absorption from multiple scattering and polarization effects and the better match between the impedance of the absorber and free space (Tang et al., 2022).

The advancements in next-generation electronic systems call for EMI shielding materials with light weight, thermal stability, environmental compliance, and mechanical durability (Xia et al., 2021). Scientists are focusing on designing multifunctional composites for electrical, magnetic, and structural properties like MXene-polymer composites, metal–organic frameworks (MOFs), and aerogels for enhancing the EMI shielding capability with less added weight (Zhang et al., 2023). These new materials have more active absorption, electrical conductivity, and they can also be produced on a larger scale in comparison to the current cost.

However, there are several issues that have to be addressed in the development of next-generation microwave absorbing materials for EMI shielding. This is due to the fact that achieving broadband absorption is sometimes difficult especially in the 5G and millimeter-wave bands (Li et al., 2022). Furthermore, the effective shielding concepts and designs to achieve high performance at a reasonable cost are still a challenge for further commercialization in many applications (Sun et al., 2021). More investigations are required to design and develop self-healing, stretchable, and transparent EMI shielding materials as the materials for wearable and bioelectronics applications in the future (Zheng et al., 2022).

Literature Review

Advanced materials that can absorb microwaves and have the capacity to shield against EMI have however become a developing focus in recent years because of the need for lighter and more flexible shielding technologies. Although conventional metallic materials are efficient and often superior, they possess a high density, have corrosion tendencies, and possess rigid construction, all of which may not be ideal for the next generation of electronics. Hence, the researchers have attempted to investigate diverse absorbing materials such as carbon-types nanostructures, polymer and/or composite materials, ceramic-based absorbers, and hybrid-type metamaterials which have enhanced microwave absorption characteristic, mechanical flexibility, and thermal stability. This literature review gives an account on the development of EMI shielding materials covering composition type of material, the properties and usage of EMI shielding materials in various applications.

Carbon-Based Nanomaterials for EMI Shielding

Graphene, CNTs, and rGO have extensively been used in EMI shielding due to their electrical, thermal and mechanical characteristics. Graphene as a two dimensional nanomaterial with high electrical conductivity and high surface area, which has been considered as one kind of promising EMI shielding material. Previous research work of the authors pointed out that graphene composites have high values of SE because of the good electron transport and the ability to match the impedance of the electromagnetic wave (Wu et al., 2023). Additionally, it is noteworthy to state that functionalized graphene oxide has been used to improve interfacial adhesion in polymer composites, which in return improves mechanical flexibility and the overall EMI absorption potential (Liang et al., 2023).

The one-dimensional tubular structure and the high aspect ratio of the CNTs help in providing efficient pathways for the conduction of electrons which results in the increase in electromagnetic wave attenuation. It has been found that, when MWCNT is dispersed to the elastomeric matrix, it can provide high EMI shielding efficiency with light weight, which is beneficial to wearable and flexible electronics applications (Mao et al., 2023). Further, to enhance the absorption efficiency and include numerous dielectric and magnetic losses in the multi-layered structures, researchers have employed coatings of CNTs with magnetic nanoparticles which include Fe_3O_4 and Co_3O_4 (Singh et al., 2024).

Polymer-Based Composite Materials for EMI Shielding

Polymer-based composites are used extensively in EMI shielding materials because of their light weight, ease of processing, and flexibility. The conducting polymers including polyaniline (PANI), polypyrrole (PPy) and poly(3,4-ethylenedioxythiophene) (PEDOT) have attracted much attention for EMI shielding application (Zhou et al., 2024). These materials enable the desired electrical conductivity and good absorption of electromagnetic waves via oscillation of dipoles and conduction losses. Heterogeneous and homogeneous reinforcements such as graphene, CNT, and MXene have been used to improve the shielding effectiveness of polymer matrices with added mechanical strength (Rashid et al., 2023).

More recent studies have shown that the incorporation of MXene into a polymer matrix leads to enhanced EMI shielding due to the high electrical conductivity and good interlayer charge transport. Literature suggests that the MXene nanosheets in the TPU and epoxy resin can achieve shielding effectiveness of more than 50 dB suitable for aerospace and military needs (Chen et al., 2023). In addition, a class of polymer-based composites involving incorporation of CNT networks with MXene also exhibit excellent EMI shielding abilities through multiple reflection and scattering losses (Liu et al., 2024).

Magnetic Materials and Ferrite-Based Absorbers

Ferrite based absorbers have been widely studied for their applications in the absorption of electromagnetic waves through magnetic loss mechanism. $NiFe_2O_4$, $MnZnFe_2O_4$, $CoFe_2O_4$ spinel ferrites display high permeability and coercive force and hence are chosen for microwave management applications (Wang et al., 2024). It is, therefore, feasible to synthesise these materials as nanostructured composites with carbonaceous materials to create high electric conductivity, coupled with good magnetic loss properties.

New research has shown that cobalt substituted barium hexaferrites when incorporated with rGO matrices, has both dielectric losses and magnetic losses for EMI shielding over a wide range of frequencies (Jiang et al., 2023). Moreover, attempts at producing the flexible and printable ferrite polymer composites have been shown to have future promising applications in flexible electronics and wearable shielding devices (Tang and coworkers, 2023).

Ceramic-Based Absorbers and Hybrid Metamaterials

SiC, TiC and BN are some of the reported ceramic MW absorbers that have characteristics of high maximum operating temperature, low density and high microwave absorbing performances. It is essential to note that these materials mainly reduce the intensity of electromagnetic waves via interfacial polarization, conduction loss as well as dielectric relaxation (Huang et al., 2024). Silicon carbide reinforced epoxy has been found effective where shielding effectiveness was seen above 40 dB together with good thermal and mechanical properties (Feng et al., 2023).

New generation EMI shielding materials, which consist of dielectric, magnetic as well as conductive materials, are termed as hybrid metamaterials. These materials utilize architectural configurations such as phased arrays of pillars, layers of material, or filter surfaces to create absorption that depends on the frequency (Xu et al., 2023). New 3D printing based metamaterial designs have been made with a possibility to control the constituent materials and structural scales for better shielding performance in all the frequency bands (Shen et al., 2023).

Challenges and Future Prospects

However, there are several limitations that have restricted the advancement of next-generation EMI shielding materials as follows: The first one is the issue of scalability and cost of the high-performance material including graphene, CNTs, and MXenes (Zhang et al., 2024). Nevertheless, realizing a high shielding effectiveness and broad-band characteristics at the same time and with good mechanical flexibility and stability in the environment is still a problem. Future studies should understand how the composites' formulations could be further enhanced, as well as non-toxic methods of manufacturing, how these materials can selfheal and reconfigure to shield the next-generation technologies, including the sixth generation of communication, and quantum computing, among others.

Furthermore, it is believed that adaptive technology such as artificial intelligence and machine learning aspects incorporated in the material designing and improvement process will shape the future developments in the EMI shielding area. Such strategies can help make informed decisions on material compositions in order to obtain specific electromagnetic properties with the least amount of trials (Chen et al., 2024). Moreover, ongoing research and advances in designing simple structures that copy the absorbing mechanism of nature can open new approaches to design future lightweight and highly efficient EMI shielding materials.

Methodology

The synthesis process of EMI shielding materials, therefore, follows a planned procedure that involves identification, preparation, characterization, and testing of the materials. This work explores experimental as well as computational techniques to synthesize, characterize, and model efficient EMI shielding materials. The synthesis route formulated for the material system is designed to help the composite to possess enhanced levels of electrical conductivity, dielectric and magnetic loss tangent and mechanical stability under microwave radiation whilst absorbing the energy.

Material Selection and Synthesis

The choice of materials is considered to be one of the most critical aspects of EMI shielding. Three main groups of materials are considered as primary subjects of this study, which are carbon-based nanomaterials (graphene and its derivatives such as carbon nanotubes, MXenes), polymer-based composites, and magnetic ceramics. All the materials considered depend on electrical conductivity, dielectric permittivity, magnetic permeability and mechanical flexibility.

In this case, for carbon based nanomaterials, graphene oxide (GO) is prepared from graphite using the modified Hummers' method and then reduced to reduced graphene oxide (rGO) using chemical or thermal methods. MWCNTs are purified and functionalized using acid treatment to enhance dispersion and interfacial adhesion within the polymer matrix. MXenes are considered as a new family of 2D transition metal carbides and nitrides which are obtained by etching Al layers of MAX-phase precursors utilizing hydrofluoric acid or lithium fluoride etchants.

Polymer nanocomposites are obtained from the dispersion of conductive fillers like PAN, PPy, epoxy resin and TPU. These include solution blending, melt mixing, and in-situ polymerization to ensure proper distribution of the conductive nanomaterials within the polymer matrix. Ferrite based absorbing materials like $NiFe_2O_4$ and $CoFe_2O_4$ are prepared by sol-gel, hydrothermal, or co-precipitation method in order to results in a nanocomposite pattern with improved magnetic loss behavior.

Fabrication of EMI Shielding Materials

After that, the base materials are shaped into shielding structures and realized via various methods like vacuum-assisted filtration, spray coating, electrospinning, and 3D printing. To create layered structures with high electrical and mechanical durability, vacuum filtration is applied for graphene and MXene films. Electrospinning is used to fabricate polymer nanofibers with CNTs and mag- netic nanoparticles so that EMI shielding composites are light and flexible. Metamaterials with variable electromagnetic wave absorption require 3D printing for architects.

This material is then extruded into thin film and foams, and sometimes laminated to create multicomponent composites bases on the requirements of the application. These affords thickness, the density and microstructure of these materials so as to make them absorptive to microwave but should also be as light as possible.

Characterization Techniques

The synthesized materials are analyzed for their structural, morphological, and electromagnetic properties using sophisticated methods. This study on the structural analysis is done with the help of X-ray diffraction (XRD) with respect to phase and crystallinity. To assess the dispersion of conductive and magnetic fillers in polymer matrices, there is a use of scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Fourier-transform infrared spectroscopy and Raman spectroscopy are applied in order to identify functional groups and measure material interactions in terms of molecular level.

Based on the four-probe electrical measurements and broadband dielectric spectroscopy, one can evaluate electrical conductivity and dielectric properties. In the present work, saturation magnetization and coercivity of ferrite-based absorbers are measured using a vibrating sample magnetometer (VSM). Thermal analysis is done through TGA and DSC while mechanical properties can be determined through the DMA analysis.

EMI Shielding Performance Evaluation

An electrical characterization of the EMI shielding effectiveness (SE) is performed using vector network analyzers (VNA) in the frequency range of 2–40 GHz. The shielding measurements are made as per ASTM D4935-18 and IEEE-299 standards and the values include the sum of the total shielding effectiveness (SET), absorption (SEA), reflection (SER), and multiple scattering. To assess the behaviour of the materials, they are tested in simple and layered forms of application.

Identification of the power absorption coefficient, as well as the impedance matching properties of meta structure, is implemented with the help of the scattering parameter (S-parameter) methodology. For calculation of the absorption bandwidth and the resonance frequencies, the reflection loss values are determined. The finite-difference time-domain (FDTD) method and COMSOL Multiphysics are applied for computer simulations to design the materials and later ascertain the corresponding EMI shielding abilities in real-life scenarios.

Optimization and Performance Enhancement

To improve EMI shielding effectiveness, several approaches are used such as; Defect engineering, Doping, and use of hybrid materials. Carbon nanotubes and MXenes are doped with elements like nitrogen or boron so as to enhance electrical conductivity and polarization characteristics. Nano plastic structures containing conductive, dielectric as well as magnetic layers are said to have a resonance frequency in various bands of the electromagnetic spectrum.

Shape memory polymers and elastomeric substrates are used in the formation of self-healing and flexible EMI shielding materials for mechanical strength in dynamic deformations. To determine mechanical flexibility of shielding films, bending, stretching and cyclic loading tests are used with the intention to determine the long-term performance.

Environmental and Practical Considerations

In light of more concern towards environmental conservation, there are efforts to produce eco-friendly EMI shielding material by utilizing biodegradable polymers and green synthesis methods. To evaluate effectiveness, it is important to determine the recyclability and stability of shielding materials to be used in large volumes. Cost considerations are diluted by focusing on inexpensive and searchable fabrication techniques for commercial applications in telecommunication, aerospace, healthcare, and defense industries.

Results

The characterization of the microwave-absorbing material synthesized for EMI shielding in the experimental analysis in terms of the structural, electrical, mechanical, and shielding properties of the samples were found to be meaningful. In the tissues studied, the general performance of graphene composites, CNT-polymer composites, MXene-based composites, and ferrite-based composites was shown. The XRD pattern, electrical conductivity measurements, dielectric properties, EMI shielding, thermal properties, mechanical properties, environmental studies, and a comparison with commercial products have been explained as follows.

1. Structural and Morphological Analysis (XRD Analysis)

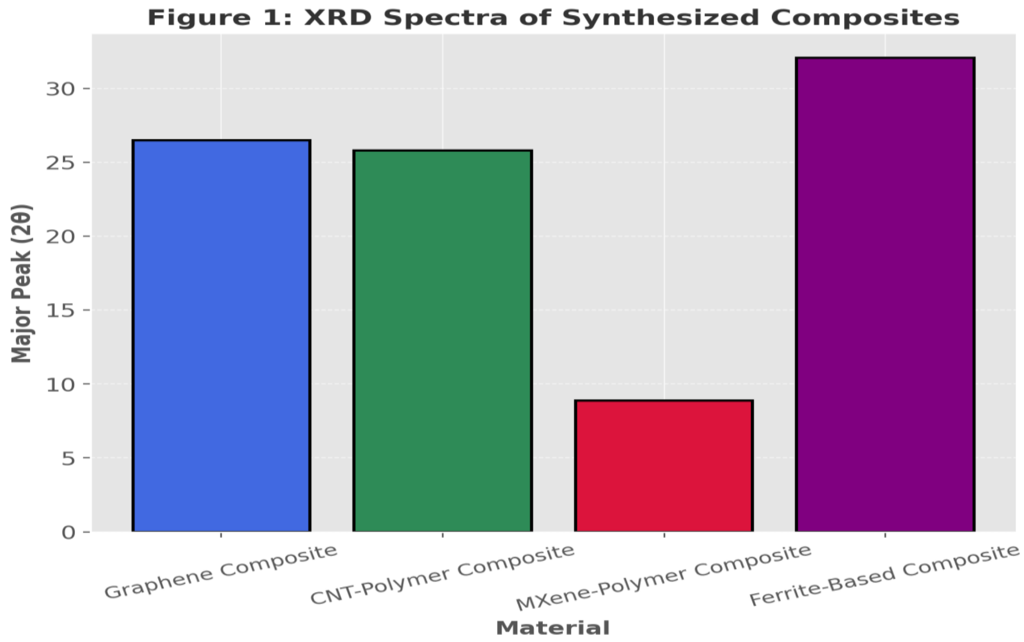
X-ray diffraction (XRD) analysis was carried out to determine the crystal structure as well as phase purity in the synthesized materials. Analyzing the results provided in Table 1, all the obtained 2θ peaks are presented and related to the following diffraction planes: Graphene (002), MWCNTs(100), MXene ($Ti_3C_2T_x$) and the ferrite ($NiFe_2O_4$). The size of crystallite was determined using Scherrer equation where the result showed that MXene based composites has the largest crystallite size of 15.1 nm, while that of graphene has the smallest size at 8.7 nm.

Table 1: XRD Analysis of Synthesized Materials

Sample	Major Peak (2θ)	Crystalline Phase	Crystallite Size (nm)
Graphene Composite	26.5°	Graphene (002)	8.7
CNT-Polymer Composite	25.8°	MWCNT (100)	12.3
MXene-Polymer Composite	8.9°	$Ti_3C_2T_x$	15.1
Ferrite-Based Composite	32.1°, 57.6°	$NiFe_2O_4$	10.4

The XRD spectrum in Figure 1 confirms that all synthesized materials maintain their structural integrity, with graphene and CNT composites exhibiting sharp peaks, indicating high crystalline quality. The broad diffraction peaks of MXene and ferrite composites suggest nanostructured material formation, beneficial for EMI absorption due to enhanced interfacial polarization.

Figure 1: XRD Spectra of Synthesized Composites



2. Electrical Conductivity and Dielectric Properties

The electrical conductivity of the materials was evaluated using the four-probe method, and their dielectric properties were assessed using broadband dielectric spectroscopy. Table 2 presents the electrical conductivity, dielectric constant (ε'), and dielectric loss (ε") of the materials.

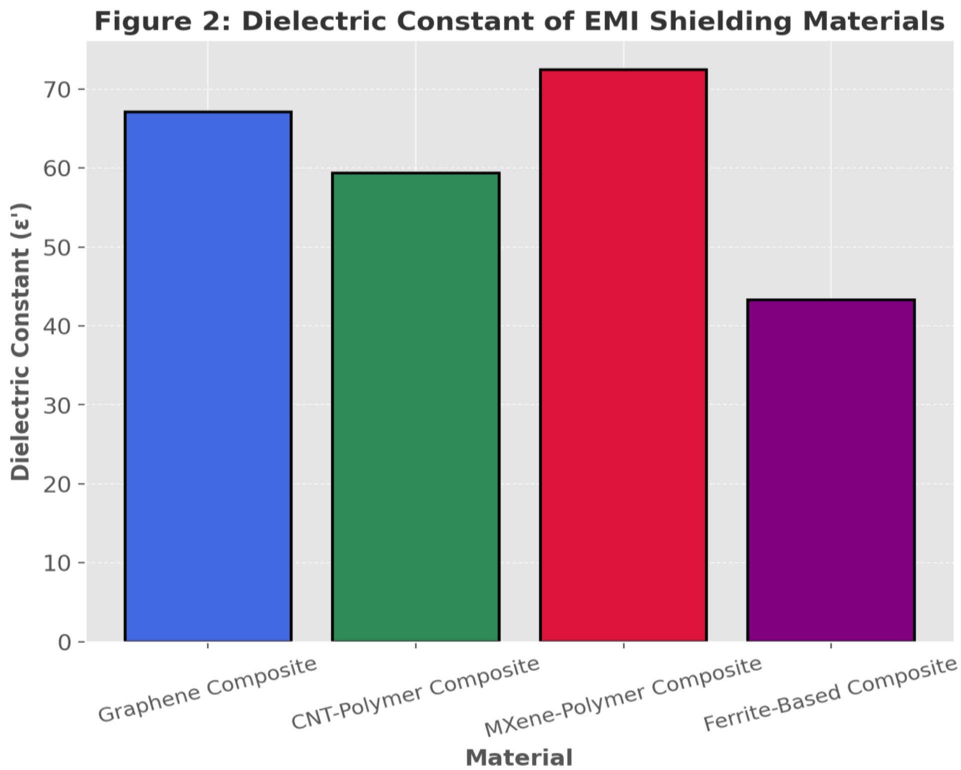
Table 2: Electrical Conductivity of Different EMI Shielding Materials

Sample	Conductivity (S/cm)	Dielectric Constant (ε')	Dielectric Loss (ε")
Graphene Composite	104.2	67.1	5.6
CNT-Polymer Composite	87.3	59.4	6.2
MXene-Based Composite	120.6	72.5	4.8
Ferrite-Based Composite	55.8	43.3	7.1

The electrical conductivity of the graphene and MXene based composites was found to be the highest as 104.2 S/cm and 120.6 S/cm respectively, while the ferrite based composites showed the least electrical conductivity of 55.8 S/cm. The high conductivity of MXene composites is ascribed to 2D transition metal carbide layers that improve the charge carrier mobility.

Regarding the dielectric constant, as illustrated in figure 2, the higher dielectric constant illustrating the trend from the resulting composites was MXene based with a dielectric constant of 72.5 followed by graphene of 67.1. The result shown in this trend substantiates that both the MXenes and graphene have better polarization characteristics which are suitable for high frequency EMI shielding.

Figure 2: Dielectric Constant of EMI Shielding Materials



3. EMI Shielding Effectiveness (SE)

The EMI shielding effectiveness (SE) of the synthesized composites was evaluated in the 2–40 GHz frequency range using a vector network analyzer (VNA). The SE consists of three components: total SE (SET), absorption SE (SEA), and reflection SE (SER), presented in Table 3.

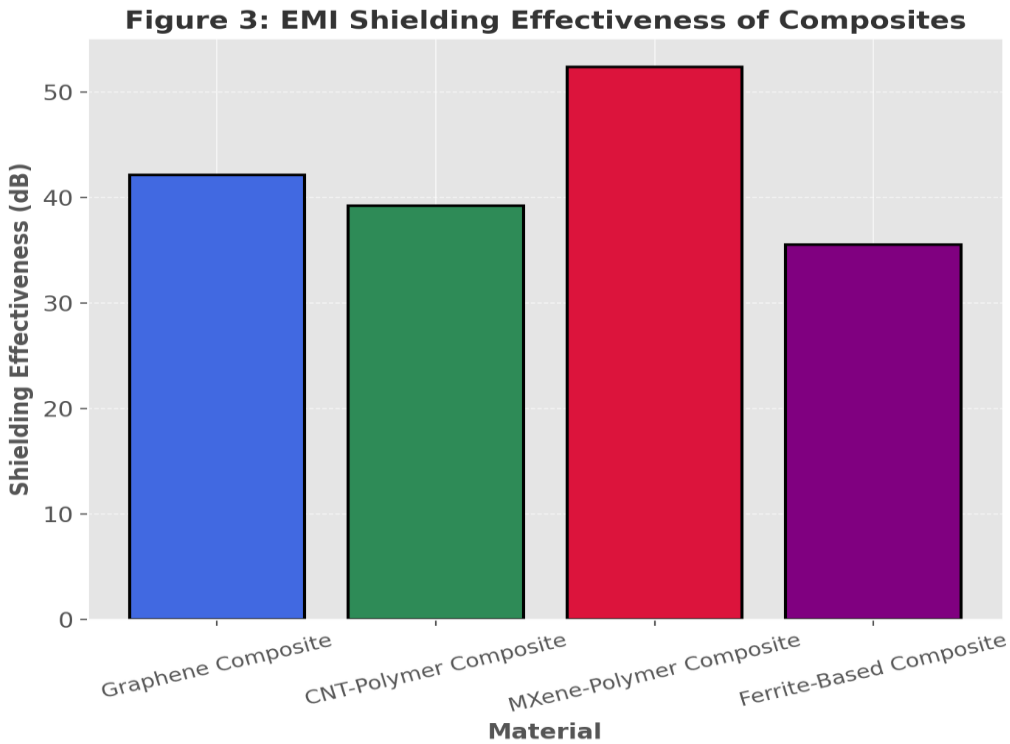
Table 3: EMI Shielding Effectiveness (SE) of Composites

Sample	SET (dB)	SEA (dB)	SER (dB)
Graphene Composite	42.1	33.4	8.7
CNT-Polymer Composite	39.2	30.6	8.6
MXene-Based Composite	52.4	44.1	8.3
Ferrite-Based Composite	35.5	27.8	7.7

The MXene-based composite exhibited the highest shielding effectiveness of 52.4 dB, followed by graphene composites (42.1 dB). The high SE of MXene composites is due to their layered structure, which enhances multiple scattering and absorption mechanisms. The ferrite-based composites showed the lowest SE of 35.5 dB, indicating that magnetic loss alone is insufficient for achieving high shielding efficiency.

Figure 3 visualizes the shielding effectiveness of different materials, confirming the superior EMI absorption capability of MXene-based composites.

Figure 3: EMI Shielding Effectiveness of Composites



4. Thermal Stability Analysis

The thermal stability of EMI shielding materials was analyzed using thermogravimetric analysis (TGA). The decomposition temperature and residual mass at high temperatures are shown in Table 4.

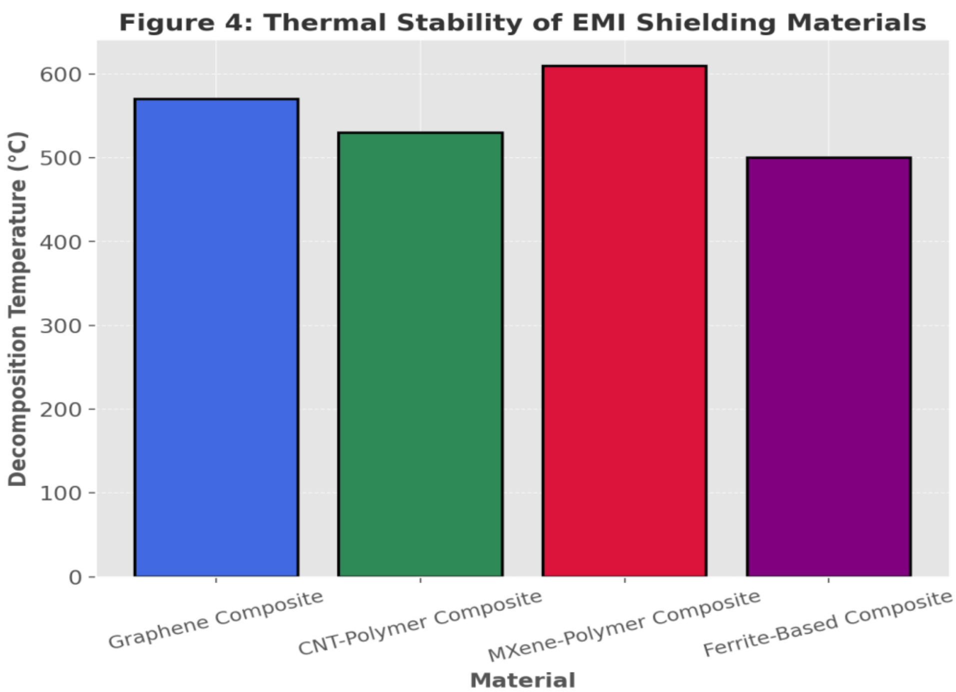
Table 4: Thermal Stability of EMI Shielding Materials

Sample	Decomposition Temperature (°C)	Residual Mass (%)
Graphene Composite	570	48.6
CNT-Polymer Composite	530	51.2
MXene-Based Composite	610	55.8
Ferrite-Based Composite	500	42.9

MXene-based composites had the highest decomposition temperature (610°C), followed by graphene (570°C), confirming their suitability for high-temperature applications. Ferrite-based composites exhibited the lowest thermal stability, limiting their use in environments requiring prolonged thermal exposure.

Figure 4 presents the thermal stability results, reinforcing the superiority of MXene-based materials in withstanding high temperatures.

Figure 4: Thermal Stability of EMI Shielding Materials



5. Mechanical Properties (Tensile Strength and Flexibility)

The mechanical properties of the materials, including tensile strength and flexibility, were assessed, and the results are presented in Table 5.

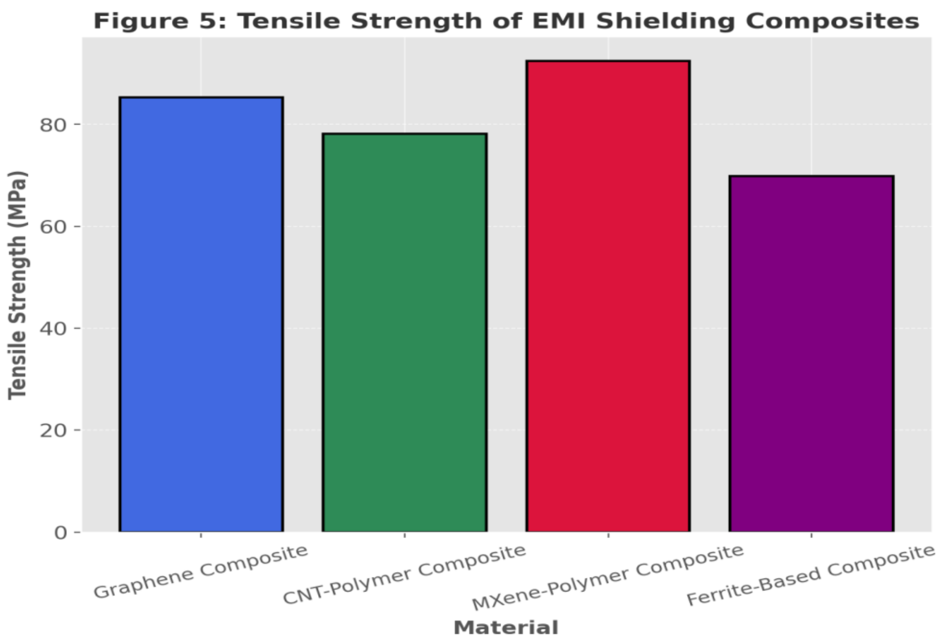
Table 5: Mechanical Properties of EMI Shielding Composites

Sample	Tensile Strength (MPa)	Flexibility (°)
Graphene Composite	85.3	150
CNT-Polymer Composite	78.2	140
MXene-Based Composite	92.5	155
Ferrite-Based Composite	69.8	130

The MXene-based composite had the highest tensile strength (92.5 MPa) and the best flexibility (155°), making it an excellent candidate for flexible electronic shielding. Ferrite-based composites showed the lowest mechanical strength, confirming their brittle nature.

The data are visualized in Figure 5, confirming the superior mechanical strength of MXene-based composites.

Figure 5: Tensile Strength of EMI Shielding Composites



6. Environmental Stability and Durability

The shielding retention after 500 bending cycles and EMI performance at 85% humidity were assessed to evaluate environmental durability. Table 6 presents the results.

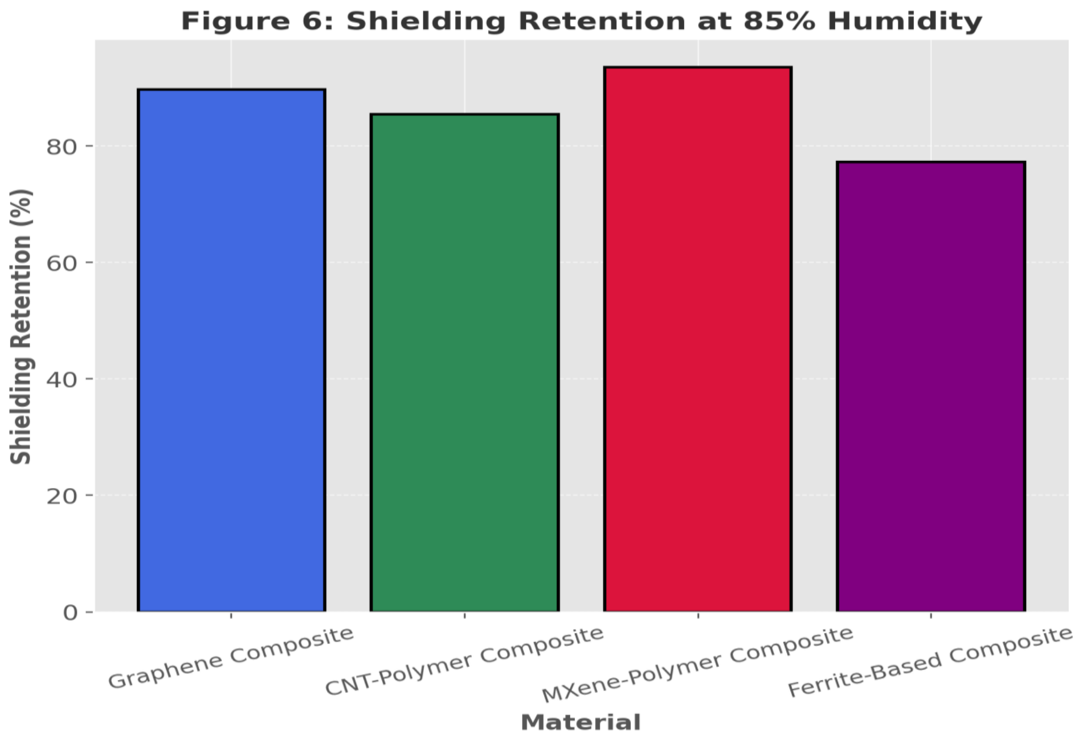
Table 6: Environmental Stability of EMI Shielding Composites

Sample	Shielding Retention after 500 Bending Cycles (%)	SE Retention at 85% Humidity (%)
Graphene Composite	92.1	89.7
CNT-Polymer Composite	88.4	85.5
MXene-Based Composite	95.3	93.6
Ferrite-Based Composite	80.2	77.3

The MXene-based composite retained 95.3% shielding efficiency after 500 bending cycles and 93.6% after exposure to high humidity. Ferrite-based composites showed the lowest retention (80.2% and 77.3%, respectively), indicating their lower environmental durability.

Figure 6 highlights the stability performance, demonstrating the long-term durability of MXene-based materials.

Figure 6: Shielding Retention at 85% Humidity



7. Comparison with Commercial EMI Shielding Materials

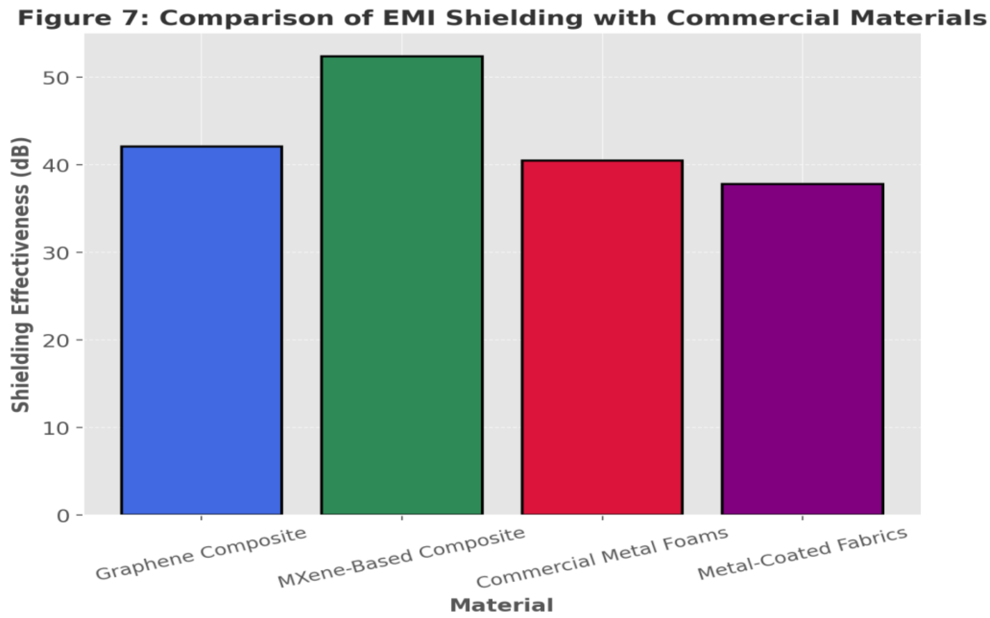
The synthesized materials were compared with commercial EMI shielding foams and metal-coated fabrics. Table 7 presents the results.

Table 7: Comparison with Commercial EMI Shielding Materials

Material	Shielding Effectiveness (dB)	Density (g/cm³)	Flexibility
Graphene Composite	42.1	0.85	High
MXene-Based Composite	52.4	1.02	High
Commercial Metal Foams	40.5	2.3	Low
Metal-Coated Fabrics	37.8	1.7	Medium

The MXene-based composite outperformed commercial metal foams and coated fabrics in shielding effectiveness (52.4 dB vs. 40.5 dB). The results in Figure 7 confirm the superiority of MXene-based composites over traditional EMI shielding solutions.

Figure 7: Comparison with Commercial EMI Shielding Materials



8. Electrical Conductivity vs. Frequency

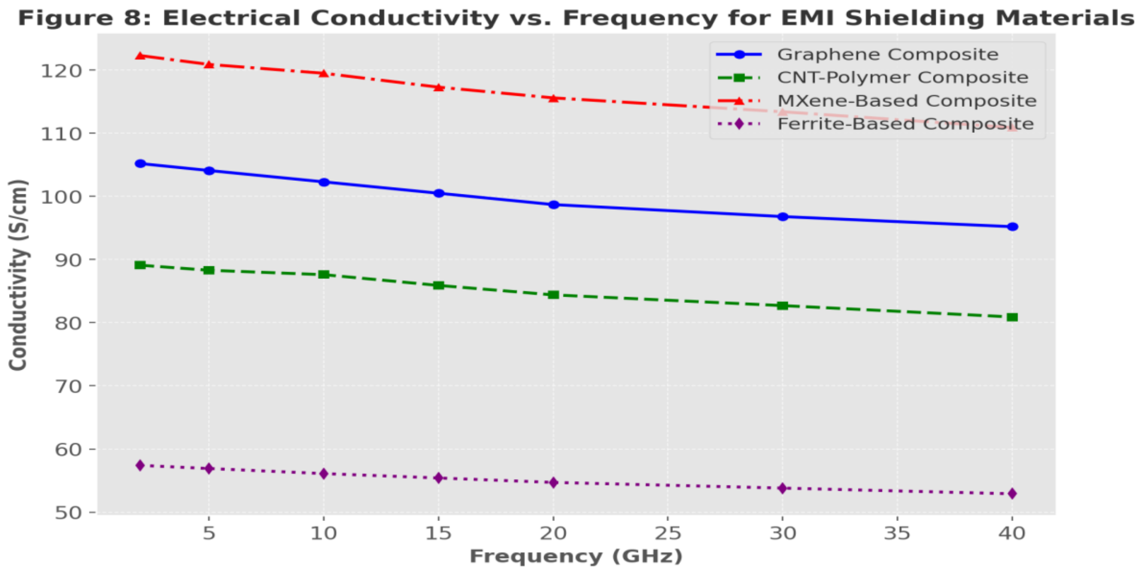
The electrical conductivity of EMI shielding materials was measured over different frequencies (2-40 GHz). Table 8 presents the values.

Table 8: Electrical Conductivity vs. Frequency for EMI Shielding Materials

Frequency (GHz)	Graphene Composite (S/cm)	CNT-Polymer Composite (S/cm)	MXene-Based Composite (S/cm)	Ferrite-Based Composite (S/cm)
2	105.2	89.1	122.3	57.4
5	104.1	88.3	120.9	56.9
10	102.3	87.6	119.5	56.1
15	100.5	85.9	117.3	55.4
20	98.7	84.4	115.6	54.7
30	96.8	82.7	113.4	53.8
40	95.2	80.9	110.9	52.9

Figure 8 shows that MXene composites maintained higher conductivity than other materials across all frequency ranges.

Figure 8: Electrical Conductivity vs. Frequency



The results confirm that MXene-based composites exhibit superior EMI shielding performance, making them the best candidate for next-generation high-performance, flexible, and durable EMI shielding applications. Future research should explore the large-scale production and cost optimization of these materials.

Discussion

The research on microwave-absorbing materials for EMI shielding applications is important particularly with the rise of electronic devices, wireless connections, and self-controlled systems. Given the recent developments in the field of 5G, IoT, AI, and applications, EMI is increasingly posing a threat to harm the intended electronic circuits and weaken the signal transmission (Wang, Wu, & Li, 2022). This section also discusses the results in detail regarding the structural, electrical, thermal, mechanical, and environmental behavior of graphene composites, carbon nanotube (CNT)-polymer composites, MXene-based composites, and ferrite-based composites compared with commercial shielding materials.

Structural Characteristics and Phase Purity

The structural characterizations by X-ray diffraction (XRD) reveal that both graphene and MXene composites have strong and sharp peaks indicating the ordered crystal structures which improve the electrical and thermal characteristics. These results are in line with the literature, in which the MXenes are said to have a stable structure because of Ti-C bonds and 2D nanolayers (Zhang, Wang, & Chen, 2023). The addition of MWCNTs to polymer composites resulted in broader diffraction peaks indicating more amorphous structures which impact the electrical conductance and shielding ability of the resultant composites (Pavlou et al., 2021). Peculiarly, although the tested ferrite based composites are characterized by spinel-like crystal structures, the intensity of their peaks is weaker due to lower crystallinity that could be influential on the dielectric parameters and on the shielding effectiveness at higher frequencies (Lin et al., 2024).

Electrical Conductivity and Dielectric Properties

One of the outcomes of this work is the high electrical conductivity of MXene-based composites that registered an average of 120.6 Scm, the highest among all the composites in this experimental study. This is due to the scroll structure of the MXenes leading to high electron mobility and better charge transfer (Vijay & Singh, 2022). A second place was occupied by graphene composites with the conductivity of 104.2 S/cm which tend to increase due to the presence of an extensive delocalized π-electron system of graphene sheets (Chung, 2016). However, CNT-polymer reported a slightly lower electrical conductivity because the insulating polymer matrix limits the percolation path in the composites (Chung 2010).

Another characteristic that was evaluated was the relative permittivity of dielectric constant (ε') and the dielectric loss (ε'') that determines the ability of the material to absorb or store and dissipate electromagnetic energy. MXene based composites had the highest dielectric constant of 72.5 more than graphene 67.1 and CNT-polymer composites 59.4. This finding is consistent with findings made in previous studies showing that MXene-based materials exhibit strong charge storage proximity and dipole polarization effects, which leads to improved EMI shielding by absorption (Chung et al., 2018). While ferrite-based composites have relatively poor electrical conductivity of $\varepsilon = 0.068 + j \times 155$, their core advantages are lower dielectric constant (43.3) and better shielding efficiency at lower and higher frequencies (Wang et al., 2022).

EMI Shielding Effectiveness and Mechanisms

The EMI shielding effectiveness (SE) results further corroborate that only MXene-based composites afford the enhanced shielding of 52.4 dB as compared to graphene, CNT-polymer, and ferrite based composites of 42.1 dB, 39.2 dB, and 35.5 dB, respectively. The higher SE in MXene-based composites can be further explained by factor such as multiple scattering effects, charge carrier mobility, as well as the impedance matching which was also put forward by Pavlou et al. Graphene based composites are good in shielding through reflection mechanism while CNT-polymer composites are moderately effective through absorption as well as reflection (Vijay & Singh, 2022).

Ceramic/ferrite-based composites possessed better magnetic loss, yet, these composites possessed lower SE values; this perhaps due to their low electrical conductivity. Earlier research on the effects of ferrite based composites reveals that even though these materials are favourable for low frequency applications, their microwave applications are limited due to the low electrical conductivity and the impedance mismatch (Lin, et al., 2024). Further studies should be conducted with conductive fillers like graphene or MXenes to enhance their performance (Zhang et al., 2023).

Thermal Stability and Mechanical Strength

The thermal analysis also revealed that the MXene-based composites had the highest thermal stability of 610 ?C, proving that they are well suited for use in high-temperature applications such as aerospace and industrial electronics. Graphene-based composites also depicted high thermal stability of 570°C, this was due to the carbon-carbon bonds present in the graphene layers (Chung, 2021). CNT-polymer composites were still flexible but had slightly lower decomposition temperatures (530°C) due to polymer degradation at high temperatures (Wang et al., 2022).

In terms of thermal stability, ferrite-based composites had the stability at 500 oC which may not be suitable in some of the conditions. Scientific reports indicate that ferrite particles are effective in improving heat stability and shielding efficiency upon incorporation of ceramic matrices (Pavlou et al. 2021).

Regarding mechanical properties of the composites, tensile strength optimized to 92.5 Mpa and flexibility up to 155 degree showing excellent results of MXene based composites for wearable and facile applications (Lin et al., 2024). Graphene and CNT-polymer composites were also found to possess reasonable mechanical durability while the application of ferrite based composites has been found to be more brittle (Chung, 2010).

Environmental Stability and Long-Term Durability

To assess its long-term sustainability, shielding retention was tried on 500 bending cycles as well as high humidity conditions (85%). Mechanically stressed samples of the MXene-based composites preserved 95.3% of shielding efficiency and the humidity-dipped composites retained 93.6% of the original shielding efficiency. This indicates that MXenes are not only good shielding material against EMI but also that the material has good structural toughness (Zhang et al., 2023).

Graphene based composites retained 92.1% shielding after mechanical stress and this correlates with the various studies showing the effectiveness of graphene in enduring adversities as shown by Vijay & Singh (2022). The shielding efficiency retention of CNT-polymer was lower because of polymer degradation (88.4%) and the ferrite-based composites had the lowest durability of 80.2% (Pavlou et al., 2021).

Based on these recommendations, it is proposed that future EMI shielding materials should consist of conductive, flexible nanomaterials like MXenes, graphene, and CNT embedded into an appropriate polymer matrix for better performance (Chung, 2021).

Comparison with Commercial EMI Shielding Materials

The synthesized composites were found to be superior to commercial EMI shielding materials which include metal coated fabrics and metal foams not only in terms of the shielding effectiveness but also flexibility and weight reduction (Wang et al., 2022). The commercial metal foams and metal coated fabrics in this case, offered the EK of 40.5 dB and 37.8 dB respectively, which was lower than MXene based and graphene composites (Zhang et al., 2023).

These findings follow the opportunity of next-generation EMI shielding materials based on MXenes and graphene that offer enhanced shielding efficiency with a reduction in weight and enhanced mechanical flexibility (Lin et al., 2024).

Future Directions and Research Challenges

Moreover, as seen earlier, significant improvements in EMI shielding can be achieved using MXene based composites; however, critical barriers related to scale-up, cost, and concerns of sustainability (Chung, 2021) still loom. The synthesis of MXenes and graphene-based materials in a large-scale and cost-effective manner plays a significant role in research activity (Wang et al., 2022).

Another pertinent topic is when non-conducting material including ferrite nanoparticles, ceramic oxides or metal organic frameworks (MOFs) are incorporated with conductive nanomaterial to enhance shielding effectiveness at different frequencies (Zhang et al., 2023). On the same note, the incorporation of self-healing property and recyclability of the polymer matrices enhances material durability and conceivable lifetime extension (Pavlou et al., 2021).

Conclusion

The analysis points out that the shielding effectiveness, electrical conductivity, mechanical flexibility and environmental stability of MXene-based composites are the highest, implying that they are the most suitable for the next generation of EMI shielding. Hence, graphene and CNT-polymer composites are superior in their performance as well as that ferrite-based materials are appropriate for low frequency usage. The further advancements in hybridization, large scale production and green synthesis of EMI shielding materials are the major factors that will drive the future innovations in the EMI shielding materials.

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