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Research paper

Electromagnetic shielding properties of polymer blended with graphene sheets and iron oxide particles

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ABSTRACT

This work introduces an innovative polymer composite for electromagnetic interference (EMI) shielding, combining recycled graphene sheets and iron oxide (Fe2O3) particles within a PVC matrix. The goal was to develop a lightweight and effective material to attenuate electromagnetic disturbances, particularly in the band frequency range (10-15 GHz). An ultra-thin (2 mm) composite containing only 10% recycled graphene, obtained from spent batteries, achieved electromagnetic shielding effectiveness (SE) of 38.5 dB in this frequency band. This result demonstrates a significant synergy between graphene and Fe2O3, where the addition of Fe2O3 enhanced graphene dispersion via ligand exchange, thereby lowering the percolation threshold and increasing wave absorption. These key findings highlight the potential of this composite for EMI shielding applications in high-stress environments. Future research perspectives include optimizing the graphene/Fe2O3 composition to further enhance shielding effectiveness, exploring the impact of different Fe2O3 morphologies, and evaluating the environmental stability and durability of the composite under various operational conditions. Furthermore, investigating the integration of this composite into specific electronic devices, such as 5G communication systems and wearable devices, will validate its practical application and commercial potential.

1. INTRODUCTION

The rise of electronic devices in our daily lives has led to increasing interest in the issue of electromagnetic interference (EMI) (Bayat et al., 2014; Miller et al., 2022). This phenomenon has

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resulted in electromagnetic pollution, causing data loss, signal interference, system failures, and growing concerns about information and communication security, as well as human health (Wang et al., 2019; Rajavel et al., 2020; Mazzoli et al., 2018).

Technological advancements have made human exposure to electromagnetic fields practically unavoidable, highlighting the need for a comprehensive understanding (Wan et al., 2020; Arjmand et al., 2012).

The distinctive characteristics of electromagnetic waves remain significantly influential, posing a notable challenge (Mueller et al., 1988). Their effects manifest in various outcomes, including alterations in physiological markers, genetic effects, and overall health. The increasing prevalence of harmful electromagnetic waves necessitates heightened vigilance to mitigate them (Liu et al., 2007; Kunkel et al., 2019). Additionally, the ability of electromagnetic waves to penetrate shielding materials at higher frequencies is a crucial factor to consider (Al-Gharram et al., 2025).

Renewable energy installations, while crucial for a sustainable future, are not without their challenges, particularly those related to electromagnetic interference (EMI) (Dincer, 2000). This interference can affect the operation of the installations themselves as well as other nearby systems, and vice versa (Williams & Amstrong, 1999). Problems with electromagnetic interference (EMI) encountered in photovoltaic solar installations (PVIs) are a growing concern due to the rapid expansion of this technology (Kane et al., 2024). These issues arise when PVIs act as sources of interference, affecting other systems (Marion & Smith, 2017). EMI emissions from PVIs can disrupt systems such as air traffic communication systems (Linder & Wiklundh, 2022), hospitals (Hut, 2019), and telephone networks (Singh et al., 2023).

Electromagnetic waves, known as electromagnetic radiation, emanate from charged particles and can pass through various media, including air, space, and matter. Metals and their composite alloys have become prominent in electromagnetic interference (EMI) shielding, where metal fillers enhance shielding effectiveness (Ortlek et al., 2012; Song et al., 2025). Metal sheets, such as copper, silver, nickel, tin, and steel, along with metal foams, are preferred due to their physical properties, such as thickness, weight, permeability, conductivity, and solderability, which affect their reflection and absorption capabilities (Ayub et al., 2021).

Previous reviews have discussed graphene and iron-reinforced polymer composites in electromagnetic interference (EMI) shielding applications, but there is still a need for deeper and more comprehensive research. Carbon-based materials, known for their exceptional conductivity and flexibility, have emerged as a leading force in the field of EMI shielding. Carbon fillers, including carbon black and carbon fibers, have played a critical role in achieving the desired shielding effectiveness (Al-Saleh et al., 2013; Rahman et al., 2023; Shetty et al., 2023).

The introduction of carbon particles and carbon nanotubes has yielded promising results (He et al., 2024). However, concerns persist regarding the limited mechanical flexibility of carbon-based materials and the corrosion and weight issues associated with metal-based counterparts (Zheng et al., 2022). Therefore, it is vital to identify a lightweight, durable, low-cost, environmentally friendly, and comprehensive shielding material, especially in light of the growing electromagnetic pollution associated with the advent of 5th generation (5G) telecommunication systems and high-frequency electronic interfaces (Huang et al., 2023; Modanwal et al., 2024).

However, our approach is distinguished by the use of recycled graphene and the introduction of Fe_2O_3 for electromagnetic shielding. This graphene exhibits several distinctive properties, including its light weight (Tiwari et al., 2020), its flexibility (Lee et al., 2015), and its excellent shielding performance (Lin et al., 2019), which makes it a suitable choice for protecting sensitive electronic components in renewable energy systems (Kausar et al., 2023). Studies have also examined the effect of iron oxide nanoparticles on electromagnetic shielding properties (Wang et al., 2020; Kaur et al., 2012). Nevertheless, our research focuses on the specific synergy between recycled graphene and Fe_2O_3 in a PVC matrix. Studies on battery recycling and graphene extraction are also available (Fleuriault et al., 2019; Larsson et al., 2014).

2. METHODS

Polyvinyl chloride (PVC) was purchased from Aldrich (Mw = 80000 g/mol). The graphite powder (graphite rod from used batteries), dibutylsebacate (DBS), 98% H2SO4, and ferric chloride FeCl3were purchased from Aldrich, along with demineralized water.

2.1 Synthesis of Graphene G

In a conventional electrochemical process (Bouriche et al., 2022); (Bakli et al., 2022), a two-electrode configuration was utilized, with a graphite rod acting as the anode and another rod serving as the cathode within a solution of sulfuric acid (H_2SO_4). The electrolyte comprised a 100ml aqueous mixture with a volume ratio of 1:4 H_2SO_4 to H_2O. The application of a direct current (DC) voltage of 10 V resulted in the complete consumption of the graphite rod, with graphene sheets transforming within 1.5 hours. After 30 minutes, the aqueous graphene ink solution was subjected to centrifugation and multiple washes with distilled water. Subsequently, the graphene material was subjected to a 24-hour drying period at 60°C.

2.2 Grafting of iron oxide (Fe_2O_3) onto graphene (G) through a hydrothermal process

The hydrothermal method (Ma et al., 2018) was used to carry out the grafting of iron oxide (Fe_2O_3) onto graphene (G). (Tran Van et al., 2019). The process begins with the preparation of an aqueous solution of ferric chloride, specifically using 1.26 grams of $FeCl_3.6H_2O$ within 100 milliliters of water. The solution is then stirred for three and a half hours to ensure a uniform solution is achieved. Concurrently, another aqueous solution is prepared, containing 1 g of graphene (G) within 100 milliliters of water. The solution is then subjected to a 100-minute sonication process, which ensures uniform consistency. The uniform graphene solution is then introduced gradually into the first ferric chloride solution. Subsequently, a concentrated aqueous solution of sodium hydroxide (NaOH) is added meticulously, drop by drop, to the amalgamated solution. The process is accompanied by stirring to achieve a pH value of approximately 11. Once this pH level has been attained, the resulting solution undergoes vigorous stirring for a further 30 minutes. Thereafter, the solution is transferred to an autoclave and subjected to hydrothermal treatment at a temperature of 180 °C for 3 hours.

2.3 Preparation of $(PVC)_x(G\text{-}Fe)_y$ nanocomposites

The first step is to combine G/Fe_2O_3 with DBS, followed by a 15 minutes sonication period. This step is crucial for ensuring the effective dispersion of G/Fe_2O_3 and preventing its agglomeration. Subsequently, PVC is added. The resulting mixture is then poured carefully into a mold and placed in an oven for one hour and 30 minutes at a temperature of 155°C. Furthermore, to examine the influence of fillers on PVC characteristics, a series of nanocomposites is meticulously developed (Wang et al., 2020; Suma et al., 2025). The resulting compositions are outlined in Table 1 for your convenience.

3. CHARACTERIZATION TECHNIQUE

Raman spectroscopy was used to facilitate observation and characterization, enabling an analysis of the material's molecular composition and structural attributes. Our samples were subjected to detailed examination using a Renishaw spectrometer, calibrated for monochromatic laser radiation (Ar^+) at a wavelength of 514.5 nm. The X-ray diffraction (XRD) analysis provided valuable insights into the microstructure of the crystalline phases inherent in our samples. To this end, our samples were evaluated using a D8 Advance Eco diffractometer (Bruker) with a copper tube (λ = 1.54 Å). To gain further insight into the morphology and structural features of the nanocomposite samples, scanning electron microscopy (SEM) (Quanta FFG 250) was employed. In assessing the electromagnetic shielding capabilities of the (G/PVC) layers, a vector network analyzer-connected device, specifically the rectangular waveguide, proved to be a crucial instrument for measurement.

Table 1. The compositions of the various G/Fe_2O_3 composite materials.

PVC%	DBS %	G/Fe_2O_3 %
45	55	0
45	52	3
45	50	5
45	45	10

4. RESULTS AND DISCUSSION

Raman spectroscopy is an invaluable technique for discerning the characteristics of both sp^2 and sp^3 hybrid carbon atoms. It is particularly effective at elucidating the features of various carbon structures, including graphite (Fig. 1.a) and graphene (Fig. 1.b). Furthermore, the ability to distinguish between single, double, and multilayer graphene is confirmed through unique Raman patterns.

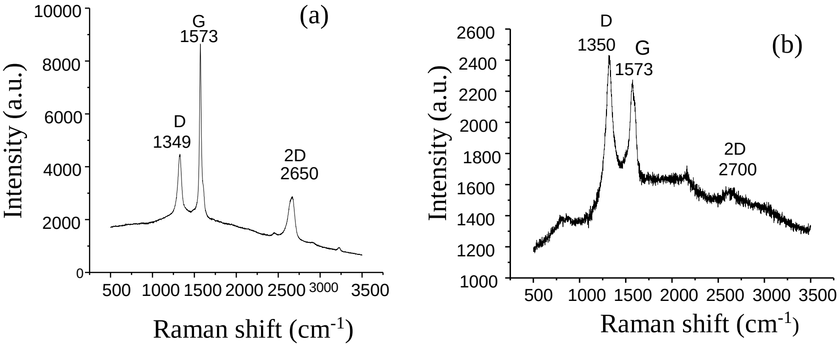

Fig 1. Raman spectra of graphite (a) and graphene (b).

The I_D/I_G ratio, which has traditionally been used to indicate inter-defect distance in graphene, has been found to have limitations when applied to graphene oxide (GO) (Kaushal et al., 2019; Chauhan et al., 2023). Chhowalla and Ferrari proposed a new amorphization trajectory, whereby the I_D/I_G ratio of carbon (sp^2) increases in line with the expansion of defects. This is linked to the square of the crystallite size (Chhowalla et al., 2000). Beaulieu et al. (2014) state that an increase in the defect intensity ratio (I_D/I_G) is indicative of an augmentation in the number of defects. A reduction in the ratio of D and G bands' intensities (I_D/I_G ratio) (Table 2), coupled with a shift towards lower wavenumbers (cm^{-1}), indicates a contraction in the extent of graphitic domains. This contraction is attributed to an increase in disorder in SP^2 bonds and a corresponding increase in SP^3 bonds within the structure. A lower I_D/I_G ratio (resembling graphite) is indicative of an intensified density of defects (Lucchese et al., 2010).

Table 2. Summary of the D and G band intensities, represented as the I_D/I_G ratio.

Sample	D -Intensity (u.a)	G -Intensity (u.a)	I_D/I_G
Graphite	4411	8565	0.52
G	2427	2260	1.07

Furthermore, the X-ray spectrum of the graphite powder (Fig. 2.a) displays a hexagonal structure consistent with the (002) orientation. This is indicated by a single peak at 2θ = 26°, which corresponds to an approximate spacing of 3.4 Å between the graphite planes.

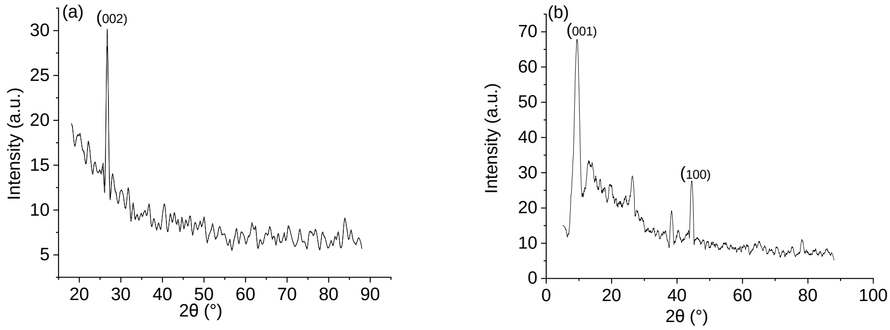

Fig 2. XRD patterns of Graphite (a) and Graphene (b)

Fig. 2.b illustrates the X-ray spectra of graphene (G), which displays a notable absence of the diffraction peak in comparison to the graphite pattern (2θ = 26.4°). This absence indicates the elimination of structural periodicity in exfoliated graphene. It is clear that the increased inter-layer spacing resulting from graphite oxidation is caused by the introduction of oxygen-containing groups between the graphite layers. This process reduces the van der Waals forces binding the layers, making them easier to separate through sonication in an aqueous medium.

Fig. 3.a illustrates the examination via scanning electron microscope (SEM), which showcases the amplification of graphite grains. This SEM image demonstrates a more uniform expansion within the milled sample. Further insight can be gleaned from Fig. 3.b, which shows our products' images vividly illustrating the dynamic configuration of graphene, confirming the presence of structural uniformity on a microscopic scale. The images portray extensive and intact graphene sheets (G) intertwined atop each other, a phenomenon that is more pronounced under higher magnification.

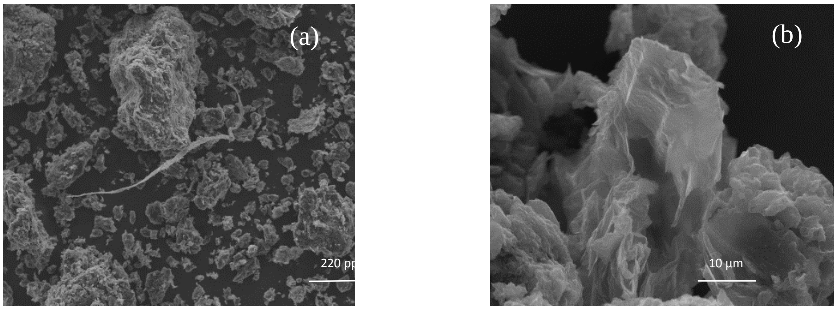

Fig 3. SEM of Graphite (a) and Graphene (b)

The FTIR spectra obtained for G, Fe_2O_3 and G/Fe_2O_3 are shown in Figure 4.

Moreover, the spectrum of G shows characteristic peaks of G from the literature, namely absorption bands at 1630 and 1530 cm^{-1}. This is attributed to C=O and C=C vibrations, respectively. The signal intensity located at 3500-3700 cm^{-1} due to the vibration of hydroxyl groups and water molecules, the peak at 1020 cm^{-1} due to bending vibration of C-OH and the peak at about 650 cm^{-1} representing ≡ C-H - groups. The spectrum of Fe_2O_3 shows bands that are the spectral signature of surface water (O-H stretching vibration near 3400 cm^{-1} and H-O-H bending vibration near 1625 cm^{-1}) and CO_2 from the air whose spectrum is near 2440 cm^{-1}. A strong absorption band (~560 cm^{-1}) exhibits the Fe–O bonding spectral signature, the only peak characteristic of hematite particles (Yun et al.,2014; Dong et al., 2010; Xu et al., 2011).

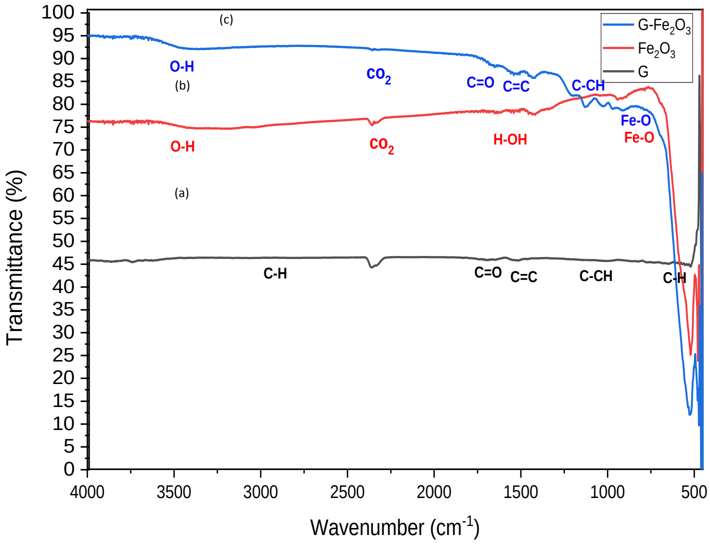

Fig 4. FTIR spectra: (a) G, (b) Fe_2O_3, (c) G-Fe_2O_3.

Furthermore, the superposition of the spectra of the G/Fe_2O_3 nanocomposite shows the band (2440 cm^{-1}). Corresponding to atmospheric CO_2, which is the two characteristic peaks of Fe_2O_3, the same absorption bands at 1630 and 1530 cm^{-1} for C=O and C=C, respectively, confirming the grafting stage (Shulga et al.,2010). To confirm the results obtained with FTIR, a complementary analysis was performed with Raman and the results obtained are shown in Figure 5.

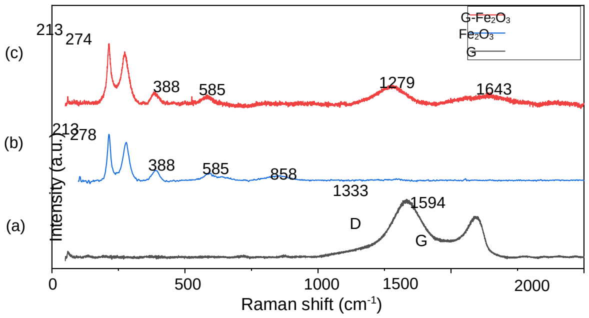

Fig 5. Raman spectra: (a) G、(b) Fe_2O_3、(c) G-Fe_2O_3.

Figure 6 illustrates the scanning electron microscopy of G-Fe_2O_3 nanoparticles. However, as shown in this figure, numerous spherical-shaped Fe_2O_3 nanoparticles at the nanoscale are observed, much better dispersed on the graphene sheets. This suggests that graphene can reduce the agglomeration of Fe_2O_3 nanoparticles.

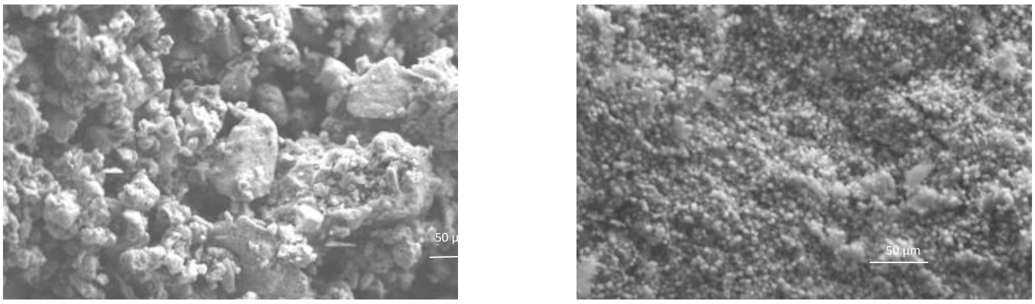

Fig 6. SEM de G-Fe_2O_3

5. EMI SHIELDING

EMI shielding materials are of great importance in the context of modern computer and telecommunications technologies (Rubežienė et al., 2020). (Bhattacharjee et al., 2020). These materials are used in a wide range of applications, including commercial and scientific electronic devices, antenna systems, and military electronics (Gadhafi et al., 2016). (García et al., 2024). In recent years, there has been a notable shift in focus towards the advancement of EMI shielding materials (Lu et al., 2024). The hybrid materials discussed earlier, comprising graphene, magnetic nanocrystals, and polymers, demonstrate a range of multifunctional attributes, including superparamagnetic behavior (Li et al., 2024). The combination of electrical and magnetic properties in materials is particularly attractive for use in electromagnetic devices (Lee et al., 2014).

EMI shielding values for various composite materials, including multifunctional carbon materials with Fe components, are detailed in Table 3.

Table 3. EMI shielding values of different composite materials

Materials	Thickness/ mm	SE/dB	Frequency/ GHz	Ref.
α-Fe_2O_3 nanoflake	5	−41.67	2.8	(Yang et al ., 2019)
Urchin like α-Fe_2O_3	1–5	−9.2	3.76–8.15	(Tong., 2011)
γ-Fe_2O_3 dendritic	4	-50	2–13	(Sun et al .,2011)
γ-Fe_2O_3 nanosphere	3	-18	14.8	(Wu et al .,2015)
Porous α-Fe_2O_3 nanosphere	2	-60	16.6	(Lv et al.,2015)
HCNT/Fe@Fe_2O_3	4	38.2	5	(Chen et al., 2019)
$ZnFe_2O_4$@graphene/TiO_2	2.5	55.5	3.8	(Wang et al., 2017)
Graphene@Fe_3O_4@WO_3@PANI	4	46.7	9.4	(Wang et al., 2017)
$NiFe_2O_4$ nanorod/graphene	2	-29.2	16.1	(Fu et al., 2013)
α-Fe_2O_3 nanorod/graphene	2	-45	12.8	(Wang et al., 2018)
Fe_3O_4//graphene	1.5	-29	8-12	(Song et al., 2015)
$ZnFe_2O_4$@graphene@TiO_2	2.5	-55.6	3.8	(Wang et al., 2017)
Cu/ graphene/epoxy	2	47	8.2–12.4	(Yanget al., 2019)

Table 3 provides an overview of the EMI shielding performance of various composite materials, highlighting the influence of composition, morphology, thickness, and frequency. It presents a wide diversity of composite materials, allowing for comparison of their shielding performance. It is observed that the morphology of Fe_2O_3 has a significant impact on shielding performance. The addition of graphene generally improves shielding performance, as seen in several composites. Shielding performance varies with frequency. Some materials are more effective at specific frequencies.

This study aims to demonstrate the potential of these multifunctional hybrid composites as candidates for electromagnetic interference (EMI) shielding materials. In this study, we evaluated the electromagnetic shielding effectiveness (EMI SE) of samples measuring 2 mm in thickness across the frequency range of 10 to 15 GHz.

Figure 7 shows the EMI shielding curves of PVC/G/Fe_2O_3 composites. As an insulator, unadulterated PVC exhibits nearly negligible EMI shielding effectiveness within the (10–15 GHz) frequency band.

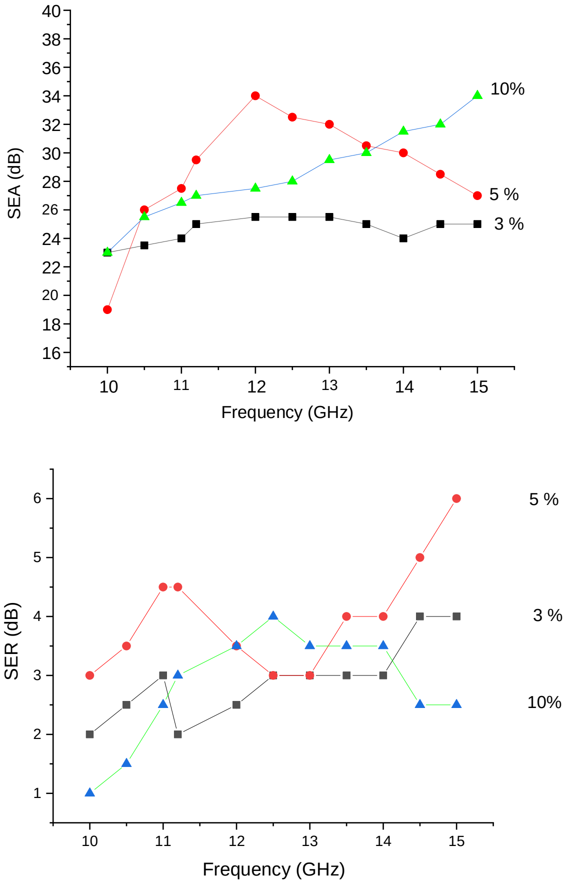

Fig 7. EMI shielding efficiency as a function of frequency measured in the 8-15 GHz range of PVC/ G/Fe_2O_3

The SEA and SER values present the shielding effectiveness obtained for PVC/graphene/Fe_2O_3 composites at different loadings in the band (10-15 GHz). According to classical electromagnetic wave theory (Ott et al., 2009) , the total shielding effectiveness (SET) of a composite is expressed in terms of the ratio of the incident power on the composite surface and the transmitted power , and can be mathematically expressed in logarithmic scale, in dB as SE=SET=SER+SEA+SEM (Al-Ghamdi et al., 2016; Bouriche al., 2022). where SER and SEA represents the contributions in total shielding effectiveness due to reflection and absorption, respectively, SEM represents the additional effects of multiple reflections and transmissions (Paul et al., 2006) and can be neglected (Al-Ghamdi et al.,2010) in all practical application .

Table 4 presents the Electromagnetic Interference (EMI) Shielding Effectiveness (SE) in decibels (dB) for PVC/graphene/Fe_2O_3 composite materials with varying weight percentages of the filler (3%, 5%, and 10%). The results are shown across three different frequency bands: 0-10 GHz, 10-12 GHz, and 12-15 GHz.

Table 4. EMI Shielding Effectiveness obtained for the PVC/graphene/Fe_2O_3 composites

Frequency Bands	SEA (dB)			SER (dB)			Max SE (dB)		
	3 %	5%	10 %	3 %	5 %	10 %	3 %	5 %	10 %
0-10 GHz	23	19	23	2	3	3.75	25	22	26.75
10-12 GHz	25	34	27	2.75	4.5	6	27.75	38.5	33
12-15 GHz	23	28	34	3.75	3.5	4.25	26.75	31.5	38.25

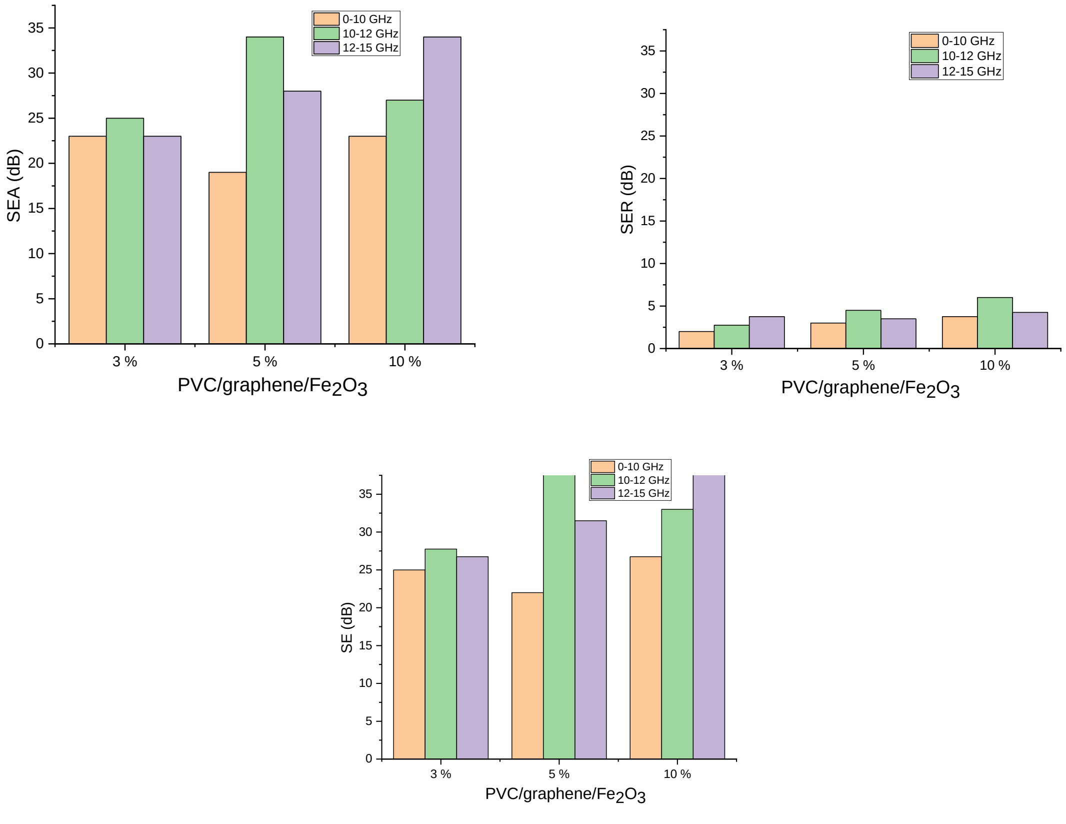

Fig 8. Column of EMI shielding efficiency as a function of frequency in the 8-15 GHz range

According to the table 4 and Figure 8, the maximum SE value increases significantly with filler content, from 3% to 5%, reaching 38.5 dB. However, a further increase in filler content to 10% results in a slight decrease in the maximum total SE, to 38.25 dB. The significant increase in the maximum SE from 3% to 5% filler content is likely due to a substantial improvement in the conductivity and permeability of the composite. The slight decrease in the maximum SE when increasing to 10% filler content could be attributed to phenomena such as the saturation of the filler's effect, particle aggregation, or complex effects related to increased interfacial reflections. This observed behavior is a result of the competition between the improvement of electromagnetic properties due to the increase in filler concentration and the negative effects that appear at higher concentrations, such as saturation and particle aggregation. The optimal point (here, 5% filler content) represents a compromise where the benefits of adding filler are maximized before the drawbacks of the high concentration become predominant.

As illustrated in Table 5, several solutions have been devised to address EMI shielding, to achieve an optimal balance between performance, cost, and applicability.

Table 5. Graphene/Fe_2O_3 and their shielding performance.

Filler Composition	Filler Loading (wt%)	Frequency Range (GHz)	Max EMI SE (dB)	Reference
Graphene oxide/Fe_2O_3	/	8.2 - 12.4	37.45	(Chen et al., 2021).
Graphene/Fe_2O_3	4 %	0.1 GHz–13.6 GHz	95.57	(Ahmad et al., 2023).
Graphene/Fe_2O_3	/	8.7 GHz	37.95	(Guo et al.,2020).
Graphene/α-Fe_2O_3	16.7 %	14.4 GHz	50.06	(Zhang et al.,2018)
Graphene/Fe_2O_3	/	7 GHz	64.3	(Chen et al.,2021)
Graphene/Fe_2O_3	3 %	10-15	28.75	This work
	5 %		40	
	10 %		38.25	

Table 5 presents a comprehensive overview of the electromagnetic interference (EMI) shielding performance of various graphene/Fe_2O_3 materials. According to this table, graphene/Fe_2O_3 composites are promising materials for shielding applications across different frequency ranges. This optimal performance results from the synergistic effects of conductive graphene and magnetic Fe_2O_3, contributing to both the reflection and absorption of electromagnetic waves.

The results of our work, applied to a slightly higher frequency range (10-15 GHz), are also presented in the table. Our data highlights the EMI shielding performance of the G-Fe_2O_3/PVC composite at different filler ratios (3%, 5%, and 10%), demonstrating that shielding effectiveness generally increases with an increase in the filler ratio within this specific composite system and frequency range.

6. CONCLUSION

The results of this study demonstrate the growing significance of composite materials in providing electromagnetic interference (EMI) protection for modern electronic applications. The production of multifunctional PVC composites involved the incorporation of graphene and Fe_2O_3 nanoparticles within the PVC matrix. The dispersion of graphene within PVC was notably enhanced through the integration of Fe_2O_3 nanoparticles, leveraging ligand exchange. This strategic approach proved highly effective, with the well-dispersed nanofillers contributing to the outstanding performance of the ternary composites. These composites demonstrated their capability to efficiently attenuate electromagnetic disturbances with exceptional electromagnetic shielding effectiveness (38.5 dB) observed in the band frequency range (10-15 GHz). Furthermore, it is expected that further optimization of the composition between graphene and Fe2O3 nanoparticles could result in significant enhancements in the efficacy of electromagnetic shielding.

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