

Absorption-Dominated EMI Shielding in Benzoxazine/Epoxy Nanocomposites Reinforced with Graphene Oxide and Zinc Oxide

Ayisha A. M. Arishi¹, Khalid A. Alamry^{2*}, Mahmoud A. Hussein³

Abstract

Benzoxazine monomer was synthesized via a Mannich condensation reaction from phenolic and amine precursors, followed by thermal curing to form a crosslinked polybenzoxazine network for advanced composite applications. Electromagnetic interference (EMI) shielding materials based on lightweight polymer nanocomposites have attracted significant attention for advanced electronic applications. In this study, benzoxazine/epoxy nanocomposites reinforced with graphene oxide (GO) and zinc oxide (ZnO) at loadings of 5 and 10 wt% were prepared and evaluated. Electrical conductivity measurements revealed a marked decrease in sheet resistance from $9.0 \times 10^7 \Omega/\text{sq}$ for the pure matrix to $5.0 \times 10^4 \Omega/\text{sq}$ for the GO 10 wt% composite, suggesting the formation of conductive pathways. In contrast, ZnO-filled composites showed only limited improvement in conductivity, consistent with their semiconducting nature. The EMI shielding effectiveness (SE) was investigated in the X-band frequency range (8–12 GHz) using a vector network analyzer. The GO 10 wt% composite achieved an average SE of approximately 19.6 dB, compared to ~16 dB and ~15 dB for GO 5 wt% and ZnO-based composites, respectively. Analysis of shielding components indicated that absorption (SEA) appears to be the dominant mechanism, while reflection (SER) remains relatively low. A practical EMF shielding test demonstrated a significant reduction in transmitted power density in the presence of the nanocomposites, supporting the trends observed in VNA measurements. However, these measurements are considered qualitative due to instrumental limitations. Overall, the results indicate that GO-reinforced benzoxazine/epoxy nanocomposites provide enhanced EMI shielding performance primarily governed by absorption mechanisms.

Keywords: Electromagnetic interference shielding, Benzoxazine/epoxy nanocomposites, absorption-dominated shielding, electrical conductivity, X-band

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Received Date: September 10, 2026

Accepted Date: October 09, 2026

Published Date: October 16, 2026

Citation: Ayisha A. M. Arishi, Khalid A. Alamry, Mahmoud A. Hussein. Absorption-Dominated EMI Shielding in Benzoxazine/Epoxy Nanocomposites Reinforced with Graphene Oxide and Zinc Oxide. Journal of Polymer & Composites. 2026; 14(5): 345–365p.

INTRODUCTION

Electromagnetic interference (EMI) has become a major challenge with the rapid development of modern electronic devices, wireless communication systems, and high-frequency technologies [1, 2]. Uncontrolled electromagnetic radiation can cause signal distortion, reduced device performance, and operational malfunction, creating an urgent need for efficient EMI shielding materials [1, 2]. The increasing integration of electronic components in aerospace systems, portable electronics, radar technologies, and telecommunication devices has further intensified electromagnetic pollution, making EMI shielding an important topic in both academic research and industrial applications. Conventional metallic materials have traditionally been used for

EMI shielding because of their excellent electrical conductivity and strong reflection capability. However, their high density, poor corrosion resistance, limited flexibility, and processing difficulties restrict their application in lightweight and portable electronic systems [1, 2]. In addition, excessive reflection of electromagnetic waves by metallic shields may lead to secondary electromagnetic pollution, which has encouraged researchers to explore absorption-dominated shielding materials with improved multifunctional performance. Consequently, polymer, polymer-based nanocomposites have emerged as promising alternatives due to their low density, ease of fabrication, corrosion resistance, and tunable electrical and dielectric properties [1–3]. Compared with conventional metals, polymer nanocomposites offer superior flexibility, lightweight characteristics, and excellent processability, making them suitable for advanced electronic and aerospace applications. The incorporation of conductive or dielectric nanofillers into polymer matrices can significantly enhance electromagnetic wave attenuation through absorption, reflection, and multiple internal reflection mechanisms [1–3]. Furthermore, the shielding effectiveness of polymer nanocomposites can be adjusted by controlling filler type, filler loading, and interfacial interactions within the polymer matrix. Such advantages have attracted increasing attention toward multifunctional polymer systems capable of simultaneously providing EMI shielding, thermal stability, and mechanical reinforcement. Among thermosetting polymers, polybenzoxazine resins have attracted considerable attention for advanced EMI shielding applications because of their excellent thermal stability, near-zero shrinkage during curing, low water absorption, flame resistance, and superior mechanical properties [4]. In addition, polybenzoxazines exhibit excellent dimensional stability and high char yield, making them suitable for high-temperature electronic and aerospace applications [5]. The excellent thermal and structural stability of benzoxazine systems is particularly important for applications involving elevated operating temperatures and harsh environmental conditions. Another important advantage of benzoxazine systems is the flexibility of their molecular design, which allows the development of multifunctional polymer composites with enhanced dielectric, thermal, and mechanical properties. By selecting different phenolic and amine precursors, the molecular structure of benzoxazine can be modified to tailor the final properties of the resulting polymer system [6]. These advantages make benzoxazine-based materials promising candidates for high-performance EMI shielding systems, particularly when combined with functional nanofillers [7, 8]. Graphene oxide (GO) is considered one of the most effective carbon-based nanomaterials for EMI shielding applications because of its layered structure, high specific surface area, and excellent electrical characteristics after functionalization. The oxygen-containing functional groups present on GO improve their compatibility with polymer matrices and facilitate the formation of conductive pathways within composite structures [9]. These conductive networks enhance electron transport and dielectric loss, thereby improving electromagnetic wave attenuation. Furthermore, the layered morphology of GO promotes multiple internal reflections and interfacial polarization, resulting in improved microwave absorption performance. The large surface area of GO also provides abundant interaction sites between the filler and polymer matrix, which contributes to improved dispersion and enhanced interfacial bonding. Recent studies have shown that graphene-based polymer composites can achieve high EMI shielding effectiveness even at relatively low filler loadings while maintaining lightweight characteristics [8]. Polybenzoxazine composites reinforced with graphene-based fillers have also demonstrated enhanced shielding performance because of improved electrical conductivity and strong interfacial interactions between the polymer matrix and nanofillers [8, 10]. In addition to improving shielding effectiveness, GO can also contribute to enhanced thermal stability and mechanical reinforcement of polymer nanocomposites. In addition to conductive carbon nanofillers, semiconductor materials – such as zinc oxide (ZnO) – have attracted increasing attention for EMI shielding and microwave absorption applications. ZnO exhibits excellent dielectric behavior, thermal stability, semiconducting characteristics, and interfacial polarization capability [11, 12]. Unlike highly conductive fillers that mainly contribute to reflection-based shielding, ZnO enhances absorption-dominated shielding through dipolar polarization and dielectric relaxation mechanisms. This absorption-oriented mechanism is particularly important because it reduces secondary electromagnetic pollution caused by reflected electromagnetic waves. Moreover, ZnO nanoparticles can improve filler dispersion and interfacial interactions within polymer matrices, leading to enhanced thermal stability and electromagnetic attenuation performance [8]. The semiconducting nature of ZnO also enables

efficient interaction with incident electromagnetic waves, which contributes to energy dissipation through dielectric loss mechanisms [13]. In addition, ZnO nanoparticles are chemically stable, cost-effective, and relatively easy to synthesize, making them attractive candidates for multifunctional EMI shielding materials. The combination of conductive carbon fillers and dielectric ceramic fillers within the same polymer matrix can, therefore, provide synergistic effects that improve both conductivity and microwave absorption behavior. Although significant progress has been achieved in polymer-based EMI shielding materials, most previous studies have mainly focused on conductive fillers and reflection-dominated shielding mechanisms. In contrast, absorption-dominated shielding behavior in benzoxazine-based systems containing both conductive and dielectric fillers remains relatively underexplored [14, 15]. Furthermore, direct comparisons between graphene oxide and zinc oxide within the same benzoxazine/epoxy matrix system are still limited. Most reported studies investigate either conductive fillers or dielectric fillers separately, while comparatively fewer studies evaluate their individual contributions under identical processing and testing conditions. Therefore, in the present study, benzoxazine/epoxy nanocomposites reinforced with graphene oxide (GO) and zinc oxide (ZnO) at loadings of 5 and 10 wt% were prepared and investigated. The EMI shielding effectiveness was evaluated in the X-band frequency range (8–12 GHz) using a vector network analyzer [14]. Electrical conductivity measurements and practical electromagnetic field attenuation tests were also conducted to correlate filler characteristics with shielding performance. Attention was devoted to identifying the dominant shielding mechanism and understanding the influence of conductive and dielectric nanofillers on electromagnetic wave attenuation.

MATERIALS AND METHODS

Materials

Bisphenol A (BPA), 4,4'-methylenedianiline (MDA), and paraformaldehyde were used for the synthesis of the benzoxazine monomer. Epoxy resin and its corresponding hardener were used as a co-matrix. Graphene oxide (GO) and zinc oxide (ZnO) nanoparticles were employed as nanofillers. All materials were used as received without further purification.

Synthesis of Benzoxazine Monomer (B-MDA)

The benzoxazine monomer (B-MDA) was synthesized via a one-pot Mannich condensation reaction. Benzoxazine monomers are typically synthesized through the reaction of phenolic compounds, primary amines, and formaldehyde via a Mannich-type mechanism [16, 17]. The molar ratio of bisphenol A:4,4'-methylenedianiline (MDA): paraformaldehyde was maintained at 1:1:4, as commonly reported for benzoxazine synthesis systems [18].

Bisphenol A (2.28 g, 0.01 mol) and 4,4'-methylenedianiline (MDA) (1.98 g, 0.01 mol) were dissolved in chloroform (CHCl_3) under continuous stirring at room temperature until a clear homogeneous solution was obtained. Subsequently, paraformaldehyde (1.20 g, 0.04 mol) was added gradually to the reaction mixture under constant stirring, following typical benzoxazine synthesis procedures [19].

The resulting mixture was then heated under reflux at 70°C for 5 h. The formation mechanism of benzoxazine involving intermediate species has been widely discussed in the literature [20]. After completion of the reaction, the solvent was removed using a rotary evaporator under reduced pressure. The obtained product was then further dried in a vacuum oven to yield the benzoxazine monomer (B-MDA) as a solid product, with an actual yield of 3.6 g (70.5%). The obtained benzoxazine monomer (B-MDA) was subsequently utilized for the fabrication of polybenzoxazine-based nanocomposites.

FTIR (ATR, cm^{-1}): 2950–2850 (aliphatic C–H stretching of methylene bridges), 1600–1500 (aromatic C=C stretching), 1230 (asymmetric C–O–C stretching of the oxazine ring), and 950–930 (oxazine ring –O–C–N– vibration). The assignments are consistent with previously reported benzoxazine systems [21, 22].

Furthermore, the ^1H NMR investigation of the synthesized B-MDA benzoxazine monomer has been illustrated in Table 1.

Table 1. ^1H NMR assignments of the synthesized benzoxazine monomer (B-MDA).

Chemical shift (ppm)	Assignment
6.5–7.5	Aromatic protons (Ar–H)
4.8–5.2	O–CH ₂ –N (oxazine ring)
3.8–4.3	N–CH ₂ –Ar
3.5–3.8	Ar–CH ₂ –Ar

Preparation of Benzoxazine-Based Nanocomposites

Benzoxazine/epoxy nanocomposites were prepared by incorporating graphene oxide (GO) or zinc oxide (ZnO) nanofillers into a benzoxazine/epoxy matrix using a solution-assisted dispersion route. Initially, 0.3 g of benzoxazine monomer was mixed with 1.0 g of epoxy resin (component A) and 1.0 g of hardener (component B) (A:B = 1:1 by weight) under continuous mechanical stirring at mild heating ($\approx 30^\circ\text{C}$) until a homogeneous matrix was obtained.

Separately, the required amount of nanofillers (5 and 10 wt% relative to the total organic matrix) was dispersed in 10 mL of chloroform (CHCl_3) under gentle heating ($\approx 30^\circ\text{C}$). The nanofiller dispersion was then slowly added dropwise to the benzoxazine/epoxy mixture under mechanical stirring, and the resulting suspension was stirred for 30 min to ensure preliminary mixing. Similar nanofiller dispersion approaches in benzoxazine-based systems have been reported in the literature [23].

The mixture was subsequently subjected to probe ultrasonication for 2 h in an ice bath to avoid overheating and to promote uniform dispersion of the GO or ZnO nanofillers throughout the benzoxazine/epoxy matrix. After sonication, the suspension was continuously stirred at room temperature overnight to allow further homogenization and partial solvent removal without additional heating.

The resulting mixture was poured into a suitable mold for sample formation and left uncovered at ambient conditions overnight to enable slow evaporation of chloroform, followed by drying in a ventilated oven at $40\text{--}50^\circ\text{C}$ for 1–2 days to remove residual solvent. The dried samples were then thermally cured in an air-circulating oven at 200°C to obtain solid nanocomposites, in accordance with reported curing conditions for benzoxazine/epoxy systems [24]. At this temperature, the benzoxazine monomer undergoes in situ thermal ring-opening polymerization [25], giving rise to a crosslinked polybenzoxazine network chemically integrated within the epoxy matrix.

Characterization Techniques

Fourier transform infrared (FTIR) spectroscopy was used to investigate the chemical structure of the synthesized benzoxazine monomer, the resulting polybenzoxazine, and their nanocomposites. The spectra were recorded in the range of $400\text{--}4000\text{ cm}^{-1}$ at room temperature using an FTIR spectrometer. Samples were analyzed using the ATR technique. The FTIR analysis was employed to identify functional groups and to monitor the ring-opening polymerization as well as the effect of nanofiller incorporation on the polymer matrix. Synthesized benzoxazine monomer (B-MDA). The spectra were recorded using a nuclear magnetic resonance spectrometer operating at an appropriate frequency (e.g., 400 MHz) in a suitable deuterated solvent – such as CDCl_3 – at room temperature. Chemical shifts (δ) were reported in parts per million (ppm) relative to the residual solvent signal. The obtained spectra were analyzed to identify the characteristic proton signals associated with the oxazine ring and methylene linkages, confirming the successful formation of the benzoxazine structure. The morphology and dispersion of nanofillers within the nanocomposites were examined using scanning electron microscopy (SEM). The electrical conductivity of the samples was evaluated using a four-point probe method at room temperature. The sheet resistance values were recorded to assess the effect of filler type and loading on electrical properties.

EMI Shielding Measurements

The electromagnetic interference (EMI) shielding effectiveness (SE) was measured using a vector network analyzer (VNA) in the X-band frequency range (8–12 GHz). The measurements were conducted using a standard WR-90 rectangular waveguide. The samples were prepared with dimensions of 22.86 mm × 10.16 mm and a thickness of approximately 2 mm. The scattering parameters (S11 and S21) were recorded. The magnitude of the scattering parameters ($|S_{11}|$ and $|S_{21}|$) was used to calculate the transmission and reflection coefficients. The total shielding effectiveness (SET), as well as absorption (SEA) and reflection (SER), were calculated accordingly. The dimensions of the samples used for VNA measurements were adjusted to fit the waveguide holder, as shown in Figure 1.

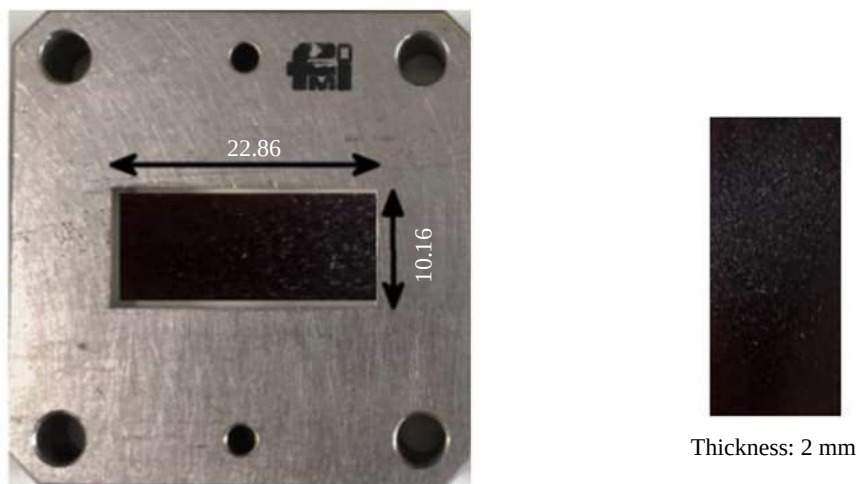


Figure 1. Photograph of the sample holder with the nanocomposite specimen (22.86 mm × 10.16 mm) used for VNA measurements in the X-band waveguide.

EMF Shielding Test

A practical electromagnetic shielding test was performed using an EMF meter to evaluate the attenuation of transmitted electromagnetic radiation. The measurements were conducted by placing the sample between the radiation source and the detector. The recorded values represent the transmitted power density. It should be noted that these measurements provide a qualitative assessment due to the limitations of the measurement setup and instrument sensitivity.

EMI Shielding Calculations

The electromagnetic interference shielding effectiveness (SE) was calculated from the measured scattering parameters ($|S_{11}|$ and $|S_{21}|$) obtained using a vector network analyzer. The transmission (T), reflection (R), and absorption (A) coefficients were determined as follows, based on standard EMI shielding equations [2]:

$$T = |S_{21}|^2$$

$$R = |S_{11}|^2$$

$$A = 1 - R - T$$

$$SE_T = -10 \log_{10}(T)$$

$$SE_R = -10 \log_{10}(1 - R)$$

$$SE_A = -10 \log_{10}\left(\frac{T}{1-R}\right)$$

where T, R, and A represent the transmission, reflection, and absorption coefficients, respectively. The total shielding effectiveness (SET), as well as absorption (SEA) and reflection (SER), were subsequently calculated.

RESULTS AND DISCUSSION

Synthesis of Benzoxazine Monomer and Polybenzoxazine-Based Nanocomposites

The synthesis route of the benzoxazine monomer (B-MDA) and its subsequent conversion into polybenzoxazine (PB-MDA) are illustrated in Figure 2. The successful formation of the benzoxazine structure was confirmed by spectroscopic analysis, as discussed in the following section.

Upon thermal curing, the benzoxazine monomer underwent ring-opening polymerization, resulting in a highly crosslinked polybenzoxazine network. Furthermore, GO and ZnO nanofillers were incorporated into the monomer matrix prior to curing, leading to the formation of polybenzoxazine-based nanocomposites. The presence of these nanofillers is expected to influence the structural and functional properties of the resulting materials.

Chemical Structure Analysis

The FTIR spectrum of the synthesized benzoxazine monomer derived from bisphenol A (BPA) and 4,4'-methylenedianiline (MDA) (B-MDA) confirms the successful formation of the oxazine ring structure (see Figure 3). The characteristic absorption band observed at approximately $930\text{--}950\text{ cm}^{-1}$ is assigned to the --O--C--N-- vibration of the oxazine ring and represents a diagnostic feature of benzoxazine structures [21]. In addition, the absorption band around 1230 cm^{-1} corresponds to the asymmetric C--O--C stretching vibration of the oxazine ring [26]. The peaks observed in the region of $2850\text{--}2950\text{ cm}^{-1}$ are attributed to aliphatic C--H stretching of methylene bridges, while bands around $1500\text{--}1600\text{ cm}^{-1}$ correspond to aromatic C=C stretching vibrations [26]. These features are consistent with benzoxazine systems synthesized via the Mannich condensation reaction involving phenols, amines, and formaldehyde [18]. Upon polymerization, significant changes in the FTIR spectrum are observed. The characteristic oxazine ring band at approximately $930\text{--}950\text{ cm}^{-1}$, clearly present in the monomer, disappears after curing, indicating the opening of the oxazine ring during the polymerization process [21]. Moreover, the absorption band around 1230 cm^{-1} shows noticeable changes, confirming the transformation of the oxazine structure into a crosslinked polybenzoxazine network [26]. In contrast, the aromatic C=C stretching bands in the region of $1500\text{--}1600\text{ cm}^{-1}$ remain relatively unchanged, indicating that the aromatic backbone is preserved during polymerization [26]. Additionally, a slight broadening in the region of $3200\text{--}3500\text{ cm}^{-1}$ may be observed after polymerization, which can be associated with structural rearrangements and hydrogen bonding within the crosslinked network. These spectral changes confirm that the curing process proceeds via thermally induced ring-opening polymerization, leading to the formation of a highly crosslinked polymer without the release of volatile byproducts [18].

The FTIR spectra of the polybenzoxazine and its nanocomposites containing graphene oxide (GO, 10%) and zinc oxide (ZnO, 10%) are presented in Figure 4. The spectrum of the neat polymer shows the absence of the characteristic oxazine ring band at approximately $930\text{--}950\text{ cm}^{-1}$, consistent with the ring-opening polymerization behavior of benzoxazine systems [21]. The band observed around 1230 cm^{-1} , assigned to C--O--C stretching vibrations, remains present in the polymer structure [26]. Upon incorporation of GO, variations in the FTIR spectrum are observed, particularly in the fingerprint region ($1000\text{--}1500\text{ cm}^{-1}$). These changes may be associated with the presence of oxygen-containing functional groups in graphene oxide, including hydroxyl, epoxy, and carbonyl/carboxyl groups, as widely reported in the literature [27, 28]. In the case of ZnO incorporation, slight spectral changes are also observed. Previous studies on ZnO/GO systems have shown that processing can modify or reduce oxygen-containing groups in GO, which is reflected in FTIR spectra [29]. Overall, the FTIR results suggest that the addition of GO and ZnO changes the local chemical environment of the polymer matrix, while FTIR alone is insufficient to determine the exact nature of the interactions.

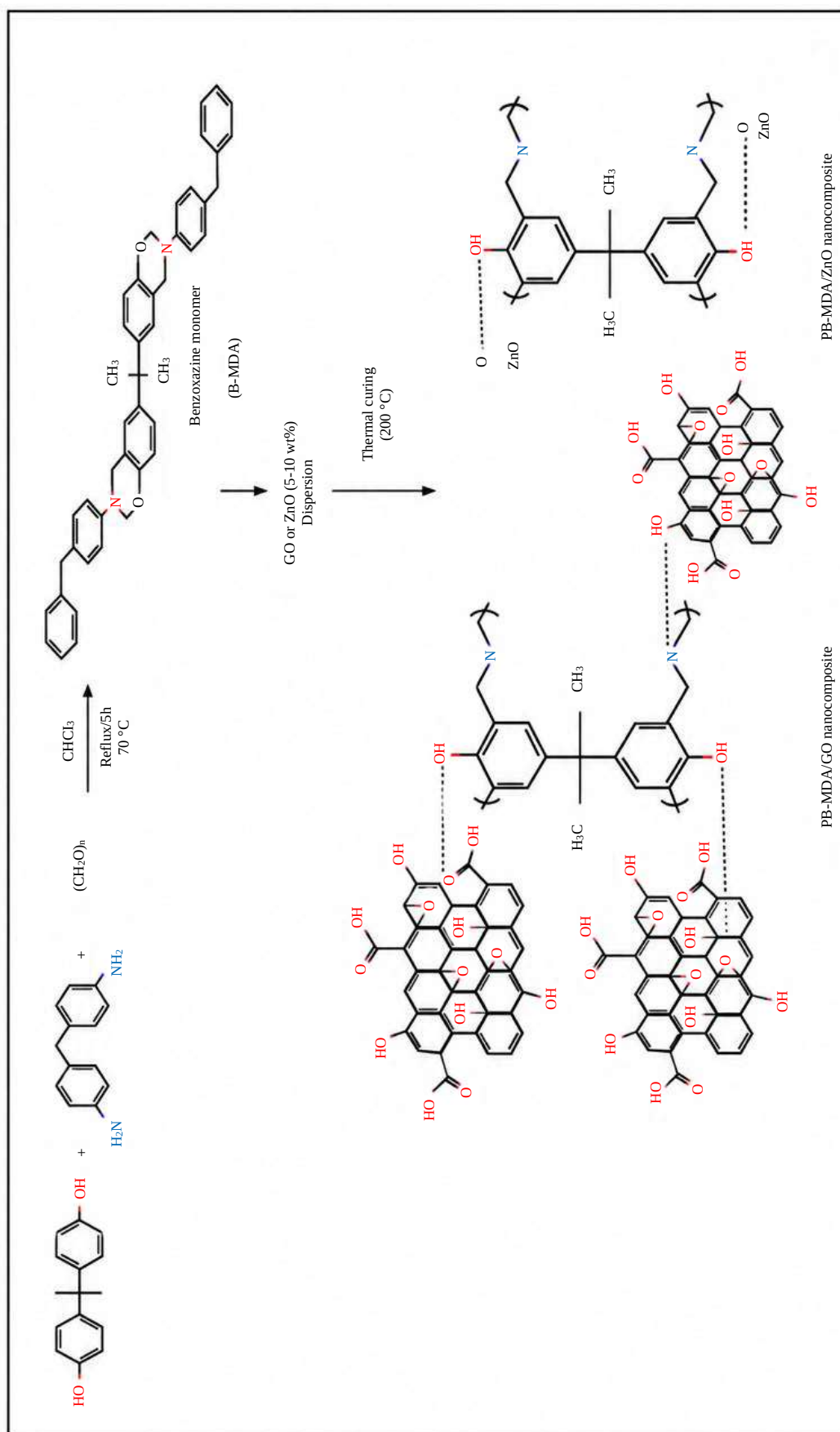


Figure 2. Synthesis of benzoxazine monomer (B-MDA), preparation of PB-MDA/GO and PB-MDA/ZnO nanocomposites via solution dispersion and thermal curing.

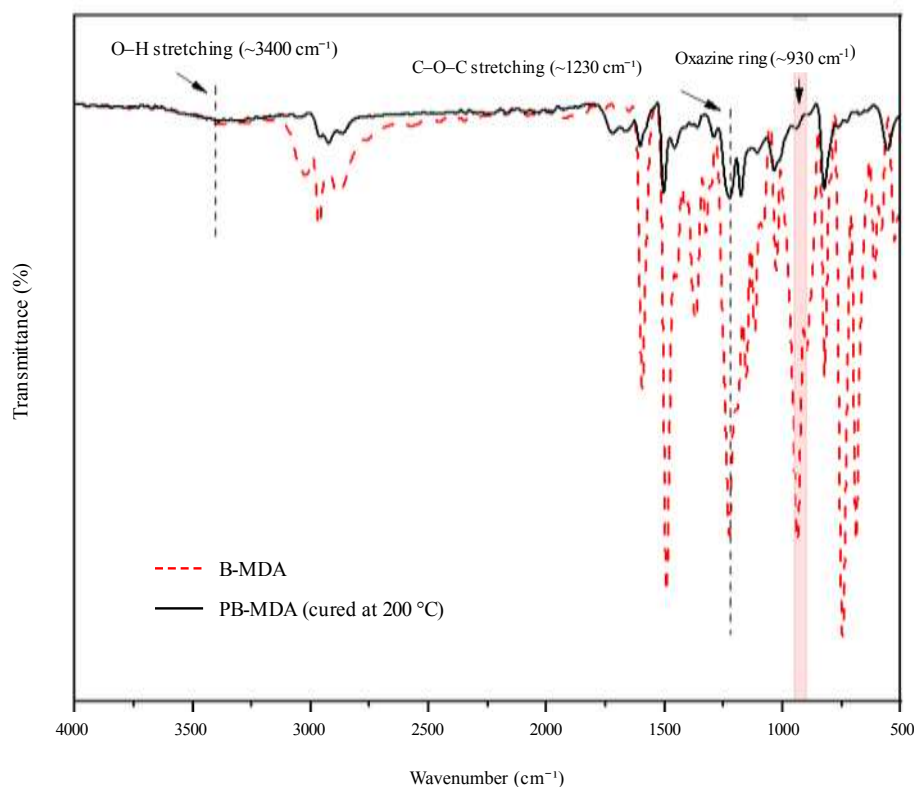


Figure 3. FTIR spectra of the benzoxazine monomer (B-MDA) and the corresponding polybenzoxazine (PB-MDA) after curing at 200°C, showing the disappearance of the characteristic oxazine band ($\sim 930\text{ cm}^{-1}$) and structural changes upon polymerization.

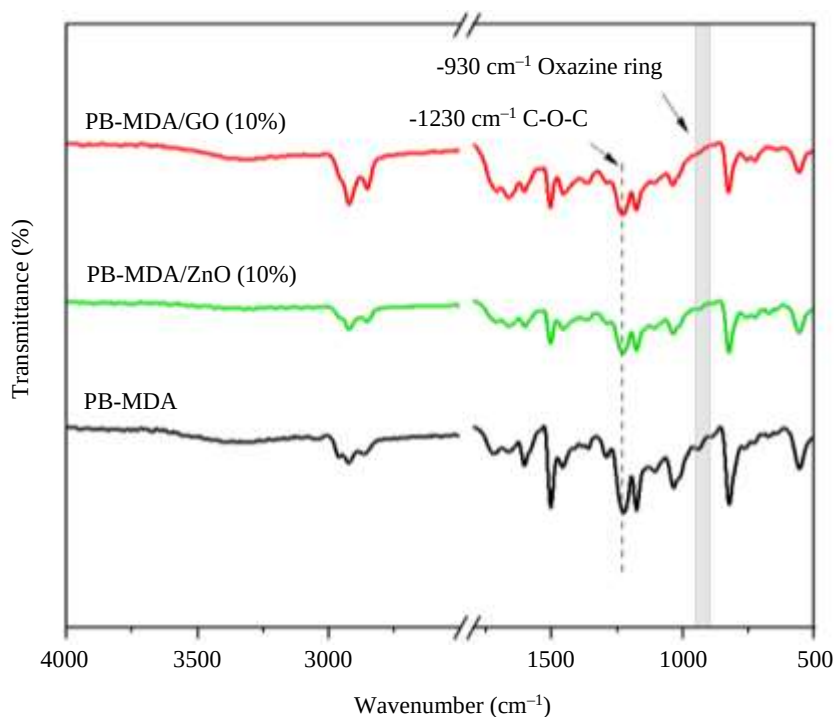


Figure 4. FTIR SPECTRA of PB-MDA and its nanocomposites containing graphene oxide (GO, 10%) and zinc Oxide (ZnO, 10%), showing changes in the fingerprint region due to the incorporation of nanofillers.

The ^1H NMR spectrum of the synthesized benzoxazine monomer confirms the successful formation of the oxazine ring structure (see Figure 5). The characteristic signal observed at approximately 4.8–5.2 ppm is assigned to the $\text{O}-\text{CH}_2-\text{N}$ protons of the oxazine ring, which is recognized as a diagnostic feature of benzoxazine compounds [21, 30]. In addition, the signal appearing in the region of 3.8–4.3 ppm corresponds to the $\text{N}-\text{CH}_2-\text{Ar}$ linkage formed during the Mannich condensation reaction, while the peak around 3.5–3.8 ppm can be attributed to methylene bridges connecting aromatic rings [21]. The aromatic protons are observed in the range of 6.5–7.5 ppm, which are characteristic of phenolic and amine-derived aromatic structures involved in benzoxazine synthesis [19, 22]. These spectral features are consistent with benzoxazine monomers synthesized from phenols, primary amines, and formaldehyde via the Mannich reaction, confirming the successful formation of the target structure [18].

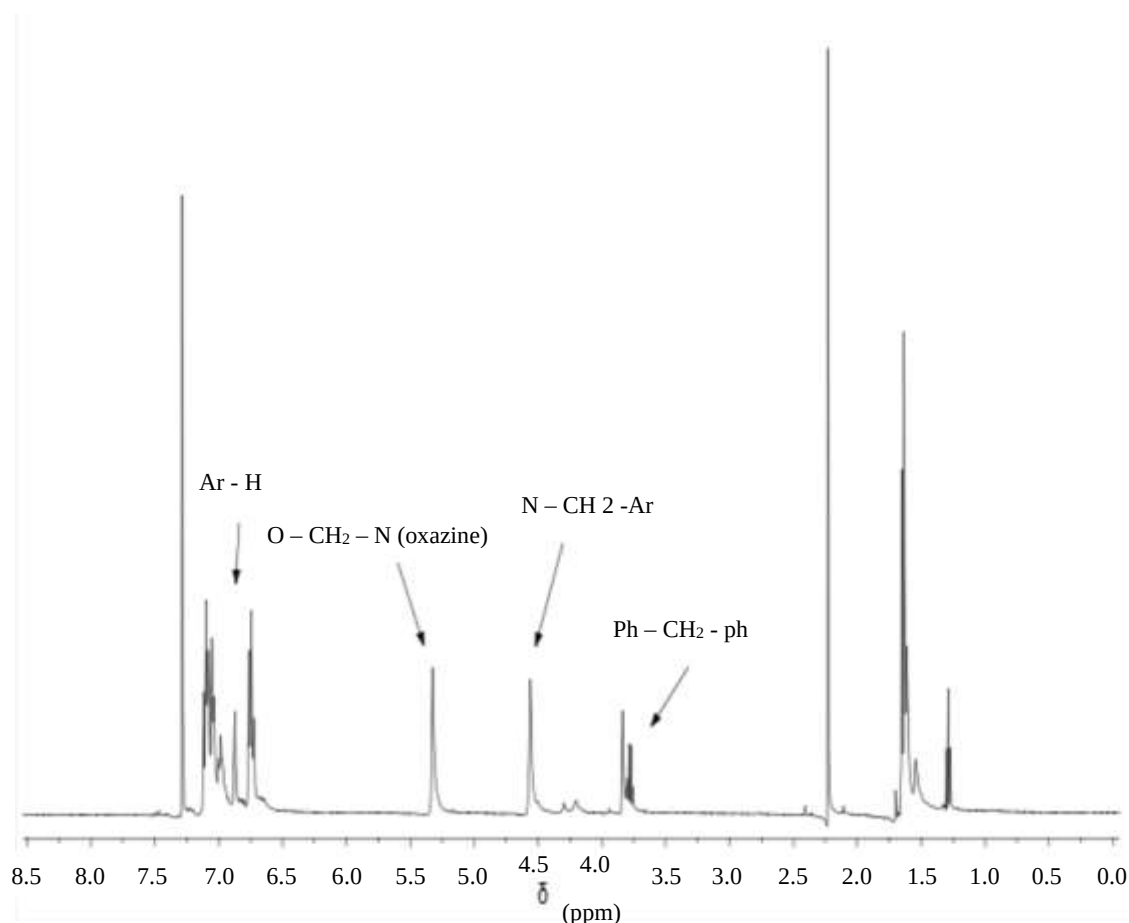


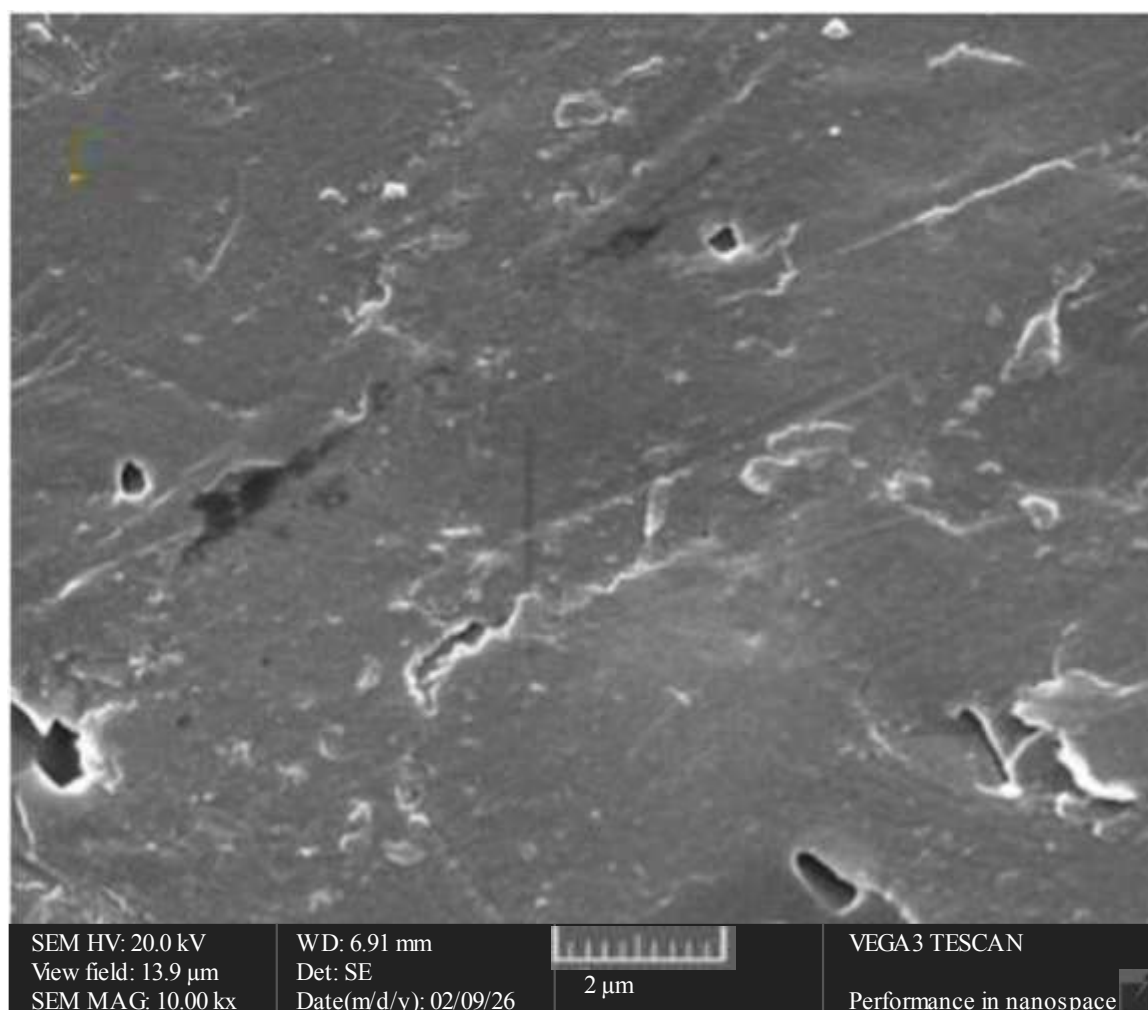
Figure 5. ^1H NMR spectrum of the synthesized benzoxazine monomer (B-MDA) showing characteristic oxazine ($\text{O}-\text{CH}_2-\text{N}$) and methylene signals.

The morphology of the benzoxazine/epoxy nanocomposites was examined using SEM at different magnifications. The GO-filled composites exhibited a sheet-like structure distributed within the polymer matrix, indicating the presence of graphene oxide layers, as shown in Figure 6 [9, 31, 32]. For the GO 10 wt% sample (Figure 6a), SEM images at 10kx magnification reveal a relatively improved dispersion of graphene oxide sheets with partially interconnected structures, suggesting the formation of conductive pathways [33, 34]. In contrast, the GO 5 wt% sample (Figure 6b) shows a less developed structure with fewer visible connections between the sheets, indicating a lower degree of network formation. In contrast, ZnO-filled composites exhibit particulate morphology. The ZnO 10 wt% sample (Figure 6c) shows a relatively uniform distribution of nanoparticles within the matrix [12], while the particles remain isolated without forming continuous structures [12]. The ZnO 5 wt% sample (Figure

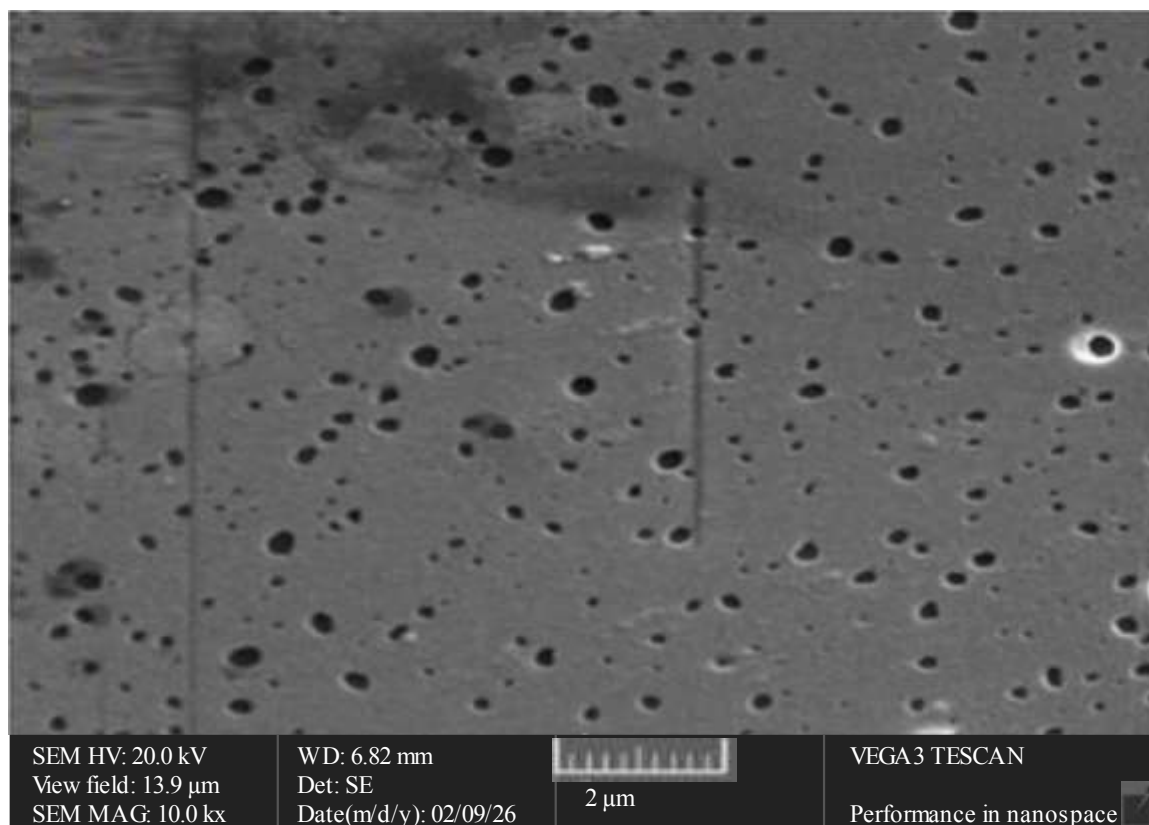
6d) displays a similar morphology with a lower particle density, indicating limited interaction between the nanoparticles. The elemental composition was further confirmed by EDX analysis (Figure 7), which shows the presence of Zn along with C, O, and N elements, confirming the successful incorporation of ZnO into the composite [12]. A higher Zn intensity is observed in the 10 wt% sample compared to the 5 wt% sample, confirming the increased filler loading. The Zn content is approximately 1.4 wt%, as summarized in Table 2, which is consistent with the relatively low Zn content in the composite and its limited contribution to electrical conductivity. These findings agree with the SEM observations (Figure 6), where ZnO nanoparticles appear as isolated particles without forming a continuous conductive network. Although a relatively uniform dispersion was observed, some localized agglomeration could be identified in both GO and ZnO-filled samples [12, 18].

Table 2. Elemental composition of benzoxazine/epoxy nanocomposites with different ZnO loadings obtained from EDX analysis.

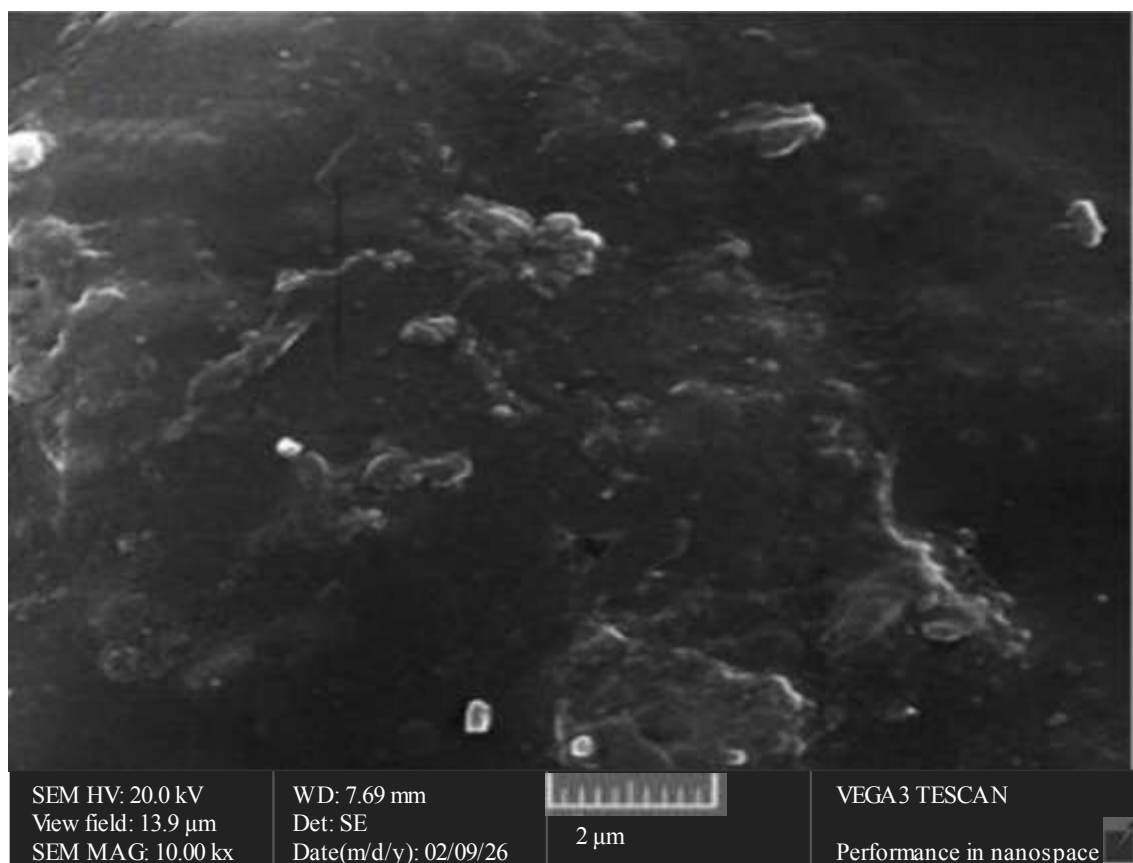
Element	Atomic No.	Mass (%) – 5 wt%	Mass (%) – 10 wt%	Atomic (%) – 5 wt%	Atomic (%) – 10 wt%
Carbon	6	69.55	70.61	75.06	76.17
Nitrogen	7	4.45	7.70	4.12	7.13
Oxygen	8	25.61	20.27	20.74	16.42
Zinc	30	0.40	1.42	0.08	0.28
Total	–	100	100	100	100



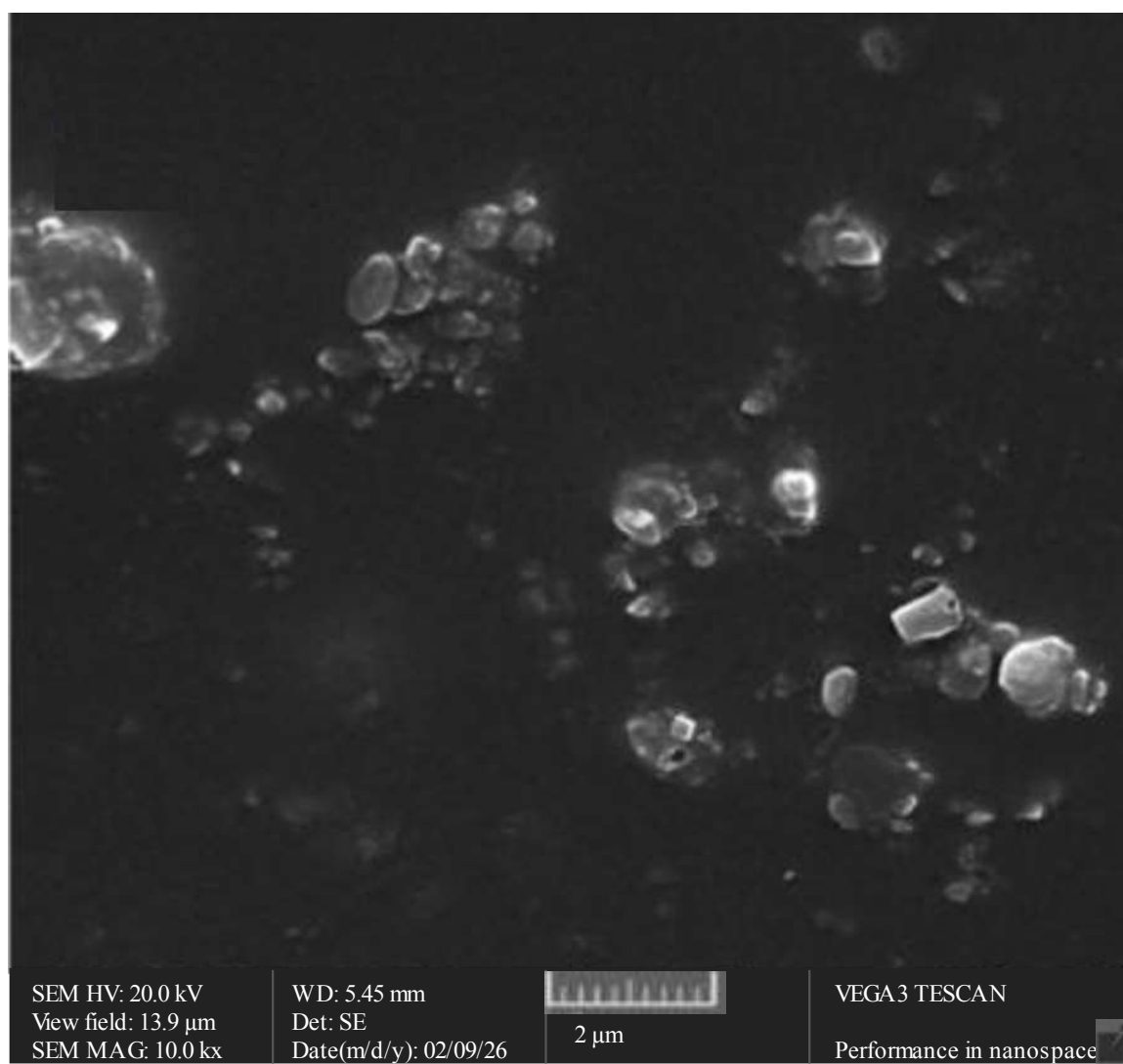
(a)



(b)

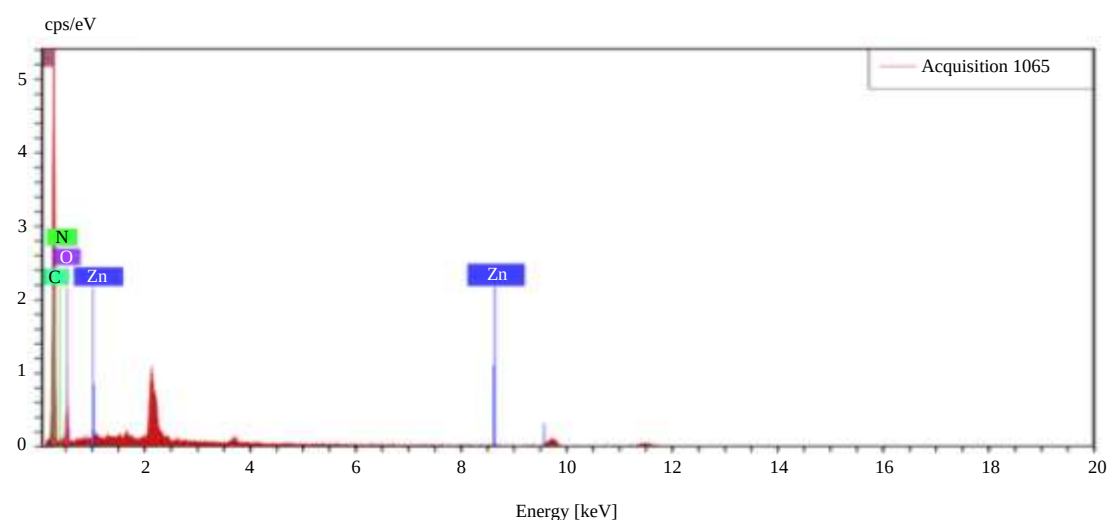


(c)

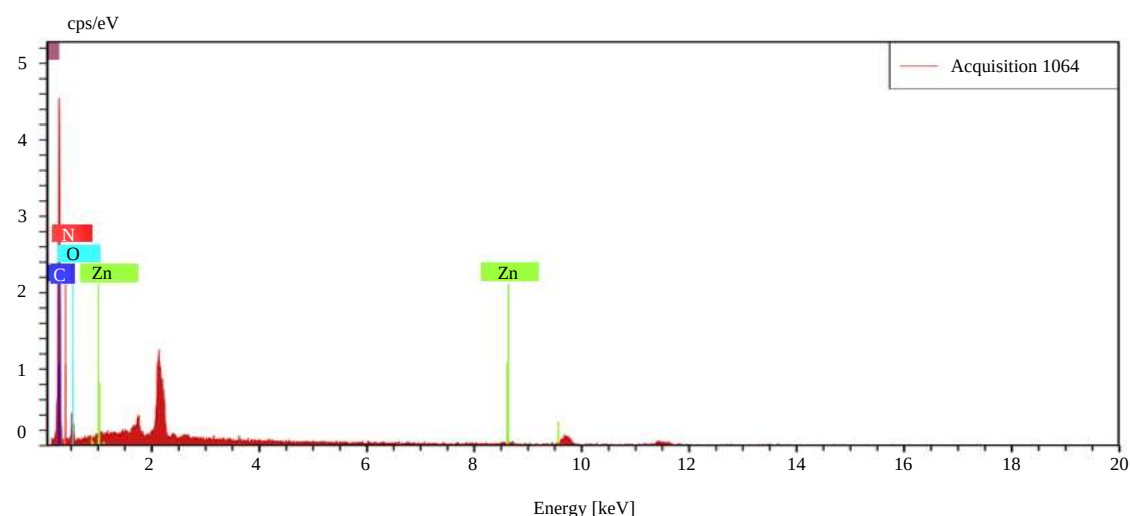


(d)

Figure 6. SEM images of benzoxazine/epoxy nanocomposites: (a) GO (10 wt%), (b) GO (5 wt%), (c) ZnO (10 wt%), and (d) ZnO (5 wt%) at 10,000 $\times$ magnification.



(a)



(b)
Figure 7. EDX Spectra of ZnO-filled benzoxazine/epoxy nanocomposites: (a) ZnO 5 wt% and (b) ZnO 10 wt%. The spectra confirm the presence of Zn along with C, O, and N elements, with higher Zn intensity observed for the 10 wt% sample.

The electrical properties of the nanocomposites were evaluated using the four-point probe method, and the results are presented in Figure 8. The pure benzoxazine/epoxy matrix exhibited a high sheet resistance of $9.0 \times 10^7 \Omega/\square$, confirming its insulating nature. Upon the addition of GO, a significant reduction in sheet resistance was observed, reaching $5.0 \times 10^4 \Omega/\square$ at 10 wt%. This reduction suggests the formation of conductive pathways at higher GO loading, enabling more efficient charge transport within the composite and resulting in a moderate improvement in electrical conductivity [33, 34]. In contrast, ZnO-filled composites showed only a moderate decrease in sheet resistance, remaining in the order of $10^7 \Omega/\square$. This behavior is attributed to the semiconducting nature of ZnO and the absence of continuous conductive networks, which is consistent with the SEM observations [12]. These results indicate that GO is more effective than ZnO in enhancing the electrical conductivity of the benzoxazine/epoxy system [12, 33, 34].

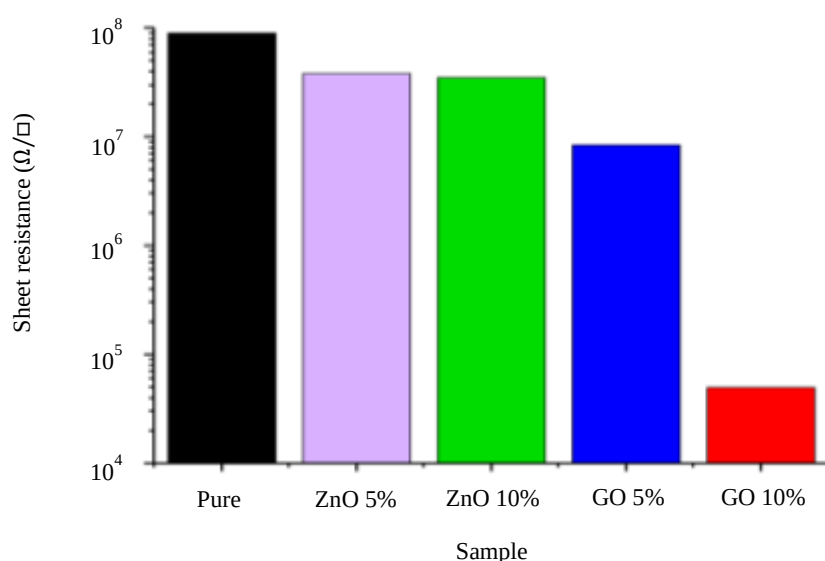


Figure 8. Sheet resistance of benzoxazine/epoxy nanocomposites with different filler types and loadings. GO-filled composites exhibit a significant reduction in sheet resistance, particularly at 10 wt%, compared to ZnO-filled samples.

The quantitative data presented in Table 3 further support the observed trend in electrical behavior. A clear inverse relationship between sheet resistance and electrical conductivity is evident, where the decrease in resistance corresponds directly to an increase in conductivity. The pure sample exhibits extremely low conductivity (1.1×10^{-7} S/cm), confirming its insulating nature. In contrast, the incorporation of GO at 10 wt% results in a substantial enhancement in conductivity (2.0×10^{-4} S/cm), which can be attributed to the formation of interconnected conductive networks within the polymer matrix [34].

Table 3. Sheet resistance and electrical conductivity of benzoxazine/epoxy nanocomposites measured using the four-point probe technique.

Sample	Sheet resistance (Ω/sq)	Conductivity (S/cm)
Pure	9.0×10^7	1.1×10^{-7}
GO (10 wt%)	5.0×10^4	2.0×10^{-4}
ZnO composites	$\sim 10^7$	$\sim 10^{-6}$

Meanwhile, ZnO-based composites show only a slight improvement in conductivity ($\sim 10^{-6}$ S/cm), which remains significantly lower than that of GO-filled samples. This limited enhancement is associated with the semiconducting characteristics of ZnO and the lack of efficient charge transport pathways. These findings clearly demonstrate that the type of nanofiller plays a crucial role in determining the electrical performance of the composites, with GO providing superior conductivity enhancement compared to ZnO.

EMI Shielding Performance

The EMI shielding effectiveness (SE) of the prepared nanocomposites was evaluated in the X-band frequency range (8–12 GHz), and the results are shown in Figure 9. The pure sample exhibited very low shielding effectiveness (~ 1 –1.5 dB), indicating minimal attenuation of electromagnetic waves. The incorporation of nanofillers led to a noticeable improvement in performance. Among all samples, the GO 10 wt% composite showed the highest SE, with values decreasing from approximately 25 dB at 8 GHz to about 18 dB at 12 GHz, and an average value of ~ 19.6 dB (Figure 10). The GO 5 wt% composite exhibited moderate performance (~ 16 dB), while ZnO-based composites showed slightly lower values (~ 14 –15 dB). A slight decrease in SE around ~ 10 GHz was observed for GO-filled samples, which may be attributed to frequency-dependent dielectric behavior or impedance mismatch effects [1, 15]. The enhanced shielding performance of GO-filled composites correlates well with the significant increase in electrical conductivity, indicating the important role of conductive pathways in EMI attenuation [1, 15, 33].

Shielding Mechanism Analysis

To further understand the shielding behavior, the total shielding effectiveness (SET) was analyzed in terms of reflection (SER) and absorption (SEA) components (Figures 11 and 12). The results indicate that absorption (SEA) is the dominant contribution to the total shielding effectiveness for all samples. In particular, the GO 10 wt% composite exhibited high absorption values (~ 19 –20 dB), while the reflection component remained relatively low (< 0.2 dB). Similar trends were observed for the other samples, although with lower overall values. The dominance of absorption over reflection suggests effective impedance matching between the composite and free space, allowing electromagnetic waves to penetrate the material and be attenuated within the internal structure [15].

GO-filled composites showed superior shielding performance due to their higher absorption capability, whereas ZnO-filled composites exhibited comparatively lower performance, mainly due to the absence of efficient conductive pathways.

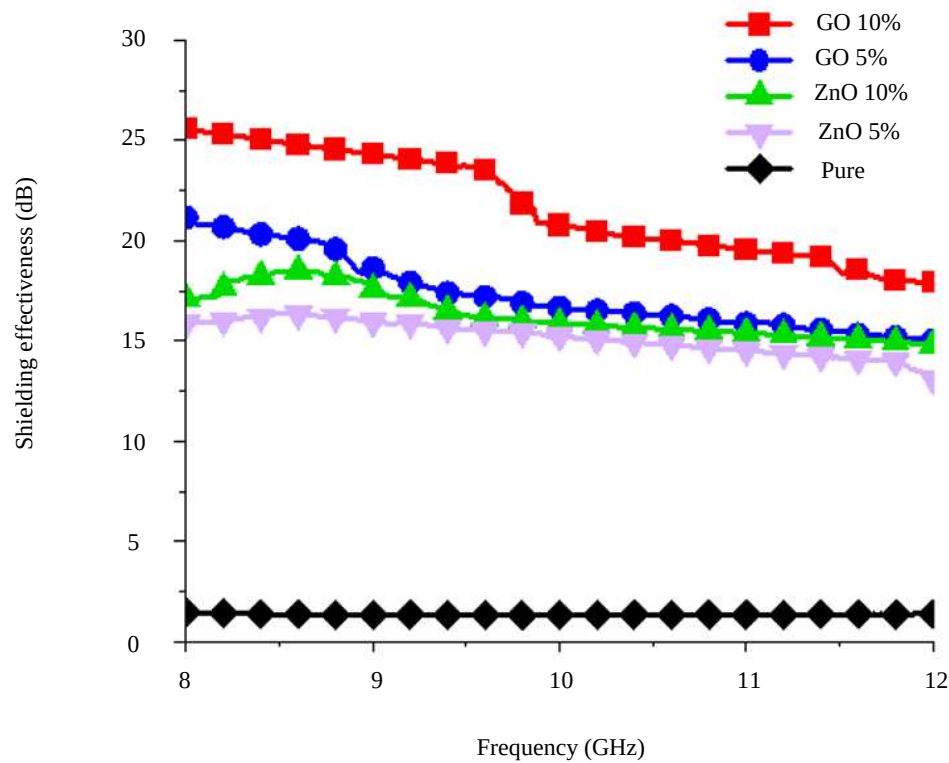


Figure 9. Frequency-dependent EMI shielding effectiveness (SE) of benzoxazine/epoxy nanocomposites in the X-band (8–12 GHz). GO-filled composites exhibit higher SE values than ZnO-filled samples, with the GO 10 wt% sample showing the highest shielding effectiveness.

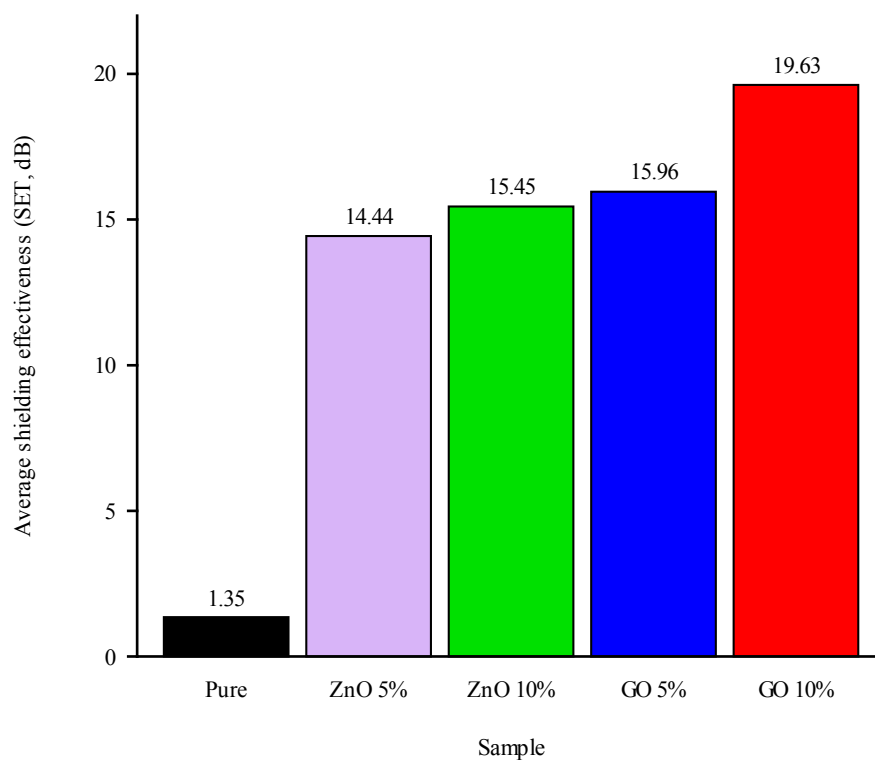


Figure 10. Average EMI shielding effectiveness (SET) of benzoxazine/epoxy nanocomposites in the X-band (8–12 GHz). GO-filled composites exhibit higher average SE values compared to ZnO-based samples, with the GO 10 wt% sample showing the highest value.

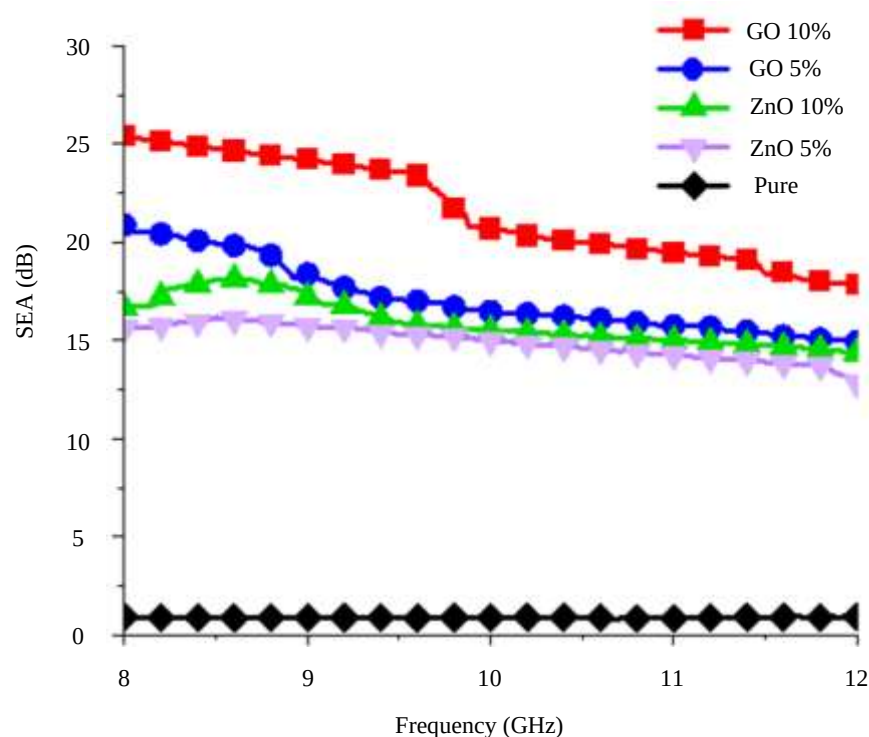


Figure 11. Absorption shielding effectiveness (SEA) of benzoxazine/epoxy nanocomposites in the X-band (8–12 GHz). GO-filled composites exhibit higher SEA values compared to ZnO-filled samples, suggesting absorption as the dominant shielding mechanism.

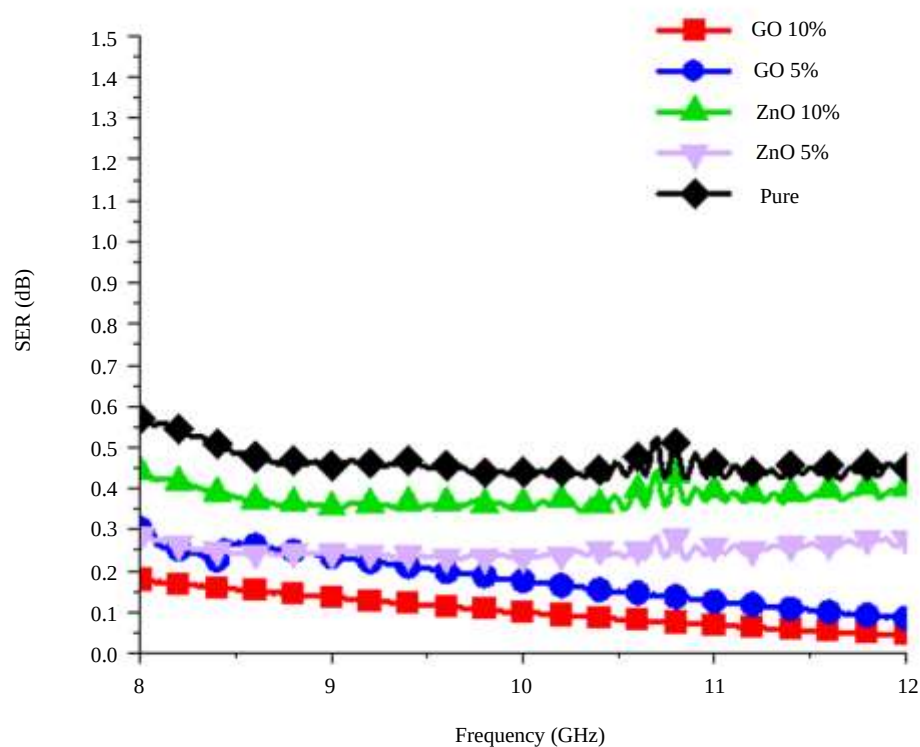


Figure 12. Reflection shielding effectiveness (SER) of benzoxazine/epoxy nanocomposites in the X-band (8–12 GHz). The reflection component remains relatively low for all samples, suggesting that absorption dominates the shielding behavior.

Proposed EMI Shielding Mechanism

As illustrated in Figure 13, and based on the obtained EMI shielding results, the electromagnetic interference (EMI) shielding performance of the developed nanocomposites arises from the combined contributions of reflection (SER), absorption (SEA), and multiple internal reflections (SEM), where the total shielding effectiveness (SET) is expressed as $SET = SER + SEA + SEM$ [35]. In this system, the contribution of multiple internal reflections (SEM) is considered minor due to the relatively high shielding effectiveness [35]. Based on the obtained results, absorption (SEA) is identified as the dominant shielding mechanism ($SEA > SER$), which is consistent with previously reported polymer-based nanocomposites [36]. Absorption-dominated EMI shielding is desirable because it attenuates electromagnetic energy within the shielding material while reducing the amount of radiation reflected into the surrounding environment. This helps minimize secondary electromagnetic interference with nearby electronic devices [37]. The reflection (R), transmission (T), and absorption (A) coefficients were calculated from the measured S-parameters using $R = |S_{11}|^2$, $T = |S_{21}|^2$, and $A = 1 - R - T$ [38]. The calculated results showed that the absorption coefficient was higher than the reflection coefficient across the investigated frequency range. In particular, GO 10 wt% exhibited A values of approximately 95.71–97.49%, compared with R values of only 0.99–4.01%, indicating that a substantially larger fraction of the incident electromagnetic energy was absorbed than reflected. This behavior is primarily attributed to the incorporation of graphene oxide (GO), which facilitates the formation of conductive networks within the polymer matrix. These networks enhance charge carrier transport and promote electron hopping, leading to increased dielectric loss and effective dissipation of electromagnetic energy [36]. In addition, significant interfacial polarization (Maxwell–Wagner–Sillars effect) occurs at the interfaces between the polymer matrix and GO nanosheets, further contributing to energy attenuation [36]. GO may provide better interfacial interaction with the polymer than pristine graphene because its oxygen-containing functional groups can interact with compatible functional groups in the polymer matrix through hydrogen bonding and other polar interactions [39]. Dipole polarization associated with the functional groups of the benzoxazine structure also plays a role in absorbing incident electromagnetic waves. Moreover, the heterogeneous microstructure of the nanocomposites induces multiple internal reflections, increasing the propagation path of electromagnetic waves within the material and enhancing the overall absorption efficiency [36]. This proposed mechanism is consistent with the experimentally observed shielding effectiveness ($SE \approx 19.6$ dB for GO at 10 wt%) and the reduction in sheet resistance, confirming that absorption is the primary contributor to EMI shielding in the developed system.

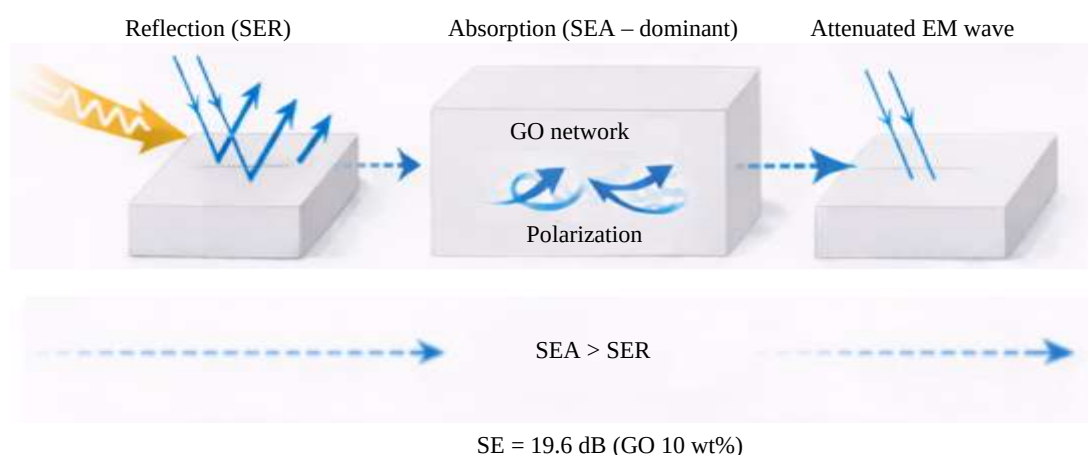


Figure 13. Schematic illustration of the EMI shielding mechanism showing reflection (SER) and dominant absorption ($SEA > SER$) in the developed nanocomposites.

Practical EMF Shielding Performance

The practical electromagnetic field (EMF) shielding performance of the nanocomposites was evaluated using a handheld EMF meter, as shown in Figure 14. The experimental setup is illustrated in Figure 15. The distance between the EMF source and the detector was maintained at approximately 10 cm, with the sample positioned midway (~5 cm from the source). The baseline measurement without shielding was approximately 1480 mW/m². Upon introducing the nanocomposite samples, a substantial reduction in transmitted EMF intensity was observed, with values decreasing to below 1 mW/m². Among all samples, the GO (10 wt%) composite exhibited the lowest value. These findings are consistent with the VNA results [15], confirming the enhanced shielding performance of GO-filled composites. However, the EMF measurements provide a qualitative assessment due to limitations in the measurement setup and instrument sensitivity [15].

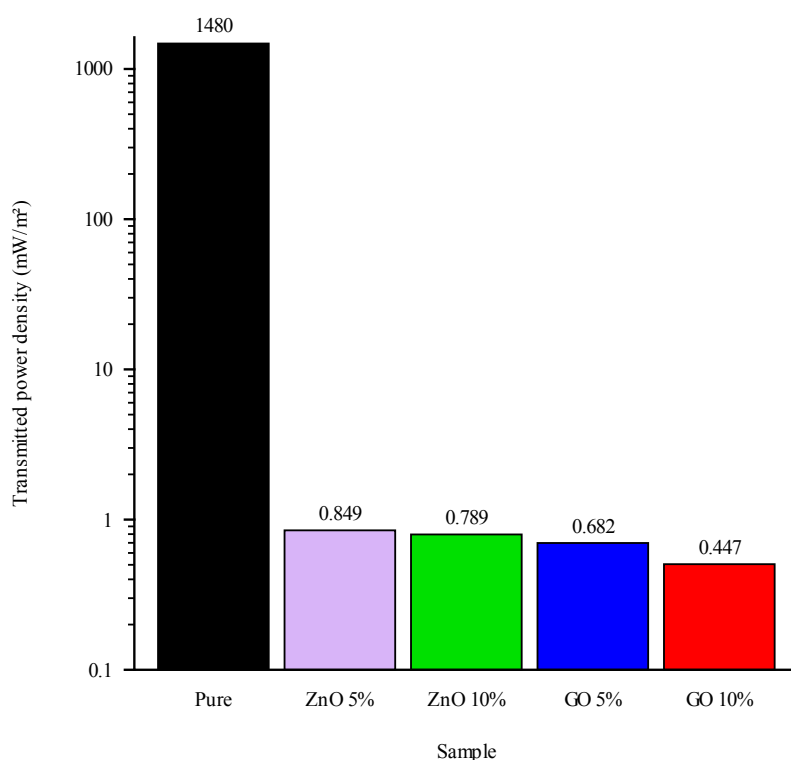


Figure 14. Transmitted EMF intensity of benzoxazine/epoxy nanocomposites measured using an EMF meter. All nanocomposites show reduced values compared to the pure sample, with GO (10 wt%) exhibiting the lowest intensity.

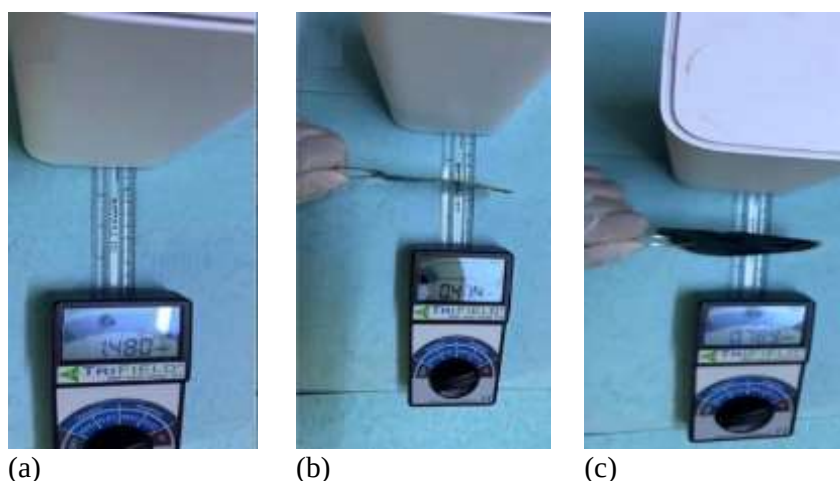


Figure 15. EMF shielding test setup using a wireless EMF source: (a) without shielding, (b) GO (10 wt%), and (c) ZnO (10 wt%). A reduction in EMF intensity is observed with nanocomposites.

CONCLUSIONS

In this study, benzoxazine/epoxy nanocomposites reinforced with graphene oxide (GO) and zinc oxide (ZnO) were successfully prepared and evaluated for electromagnetic interference (EMI) shielding applications. The incorporation of nanofillers significantly influenced both the electrical and shielding properties of the composites. The GO-filled composites exhibited a substantial reduction in sheet resistance, reaching $5.0 \times 10^4 \Omega/\text{sq}$ at 10 wt%, indicating the formation of conductive pathways. In contrast, ZnO-filled composites showed only limited improvement in electrical conductivity, consistent with the absence of continuous conductive networks. EMI shielding measurements revealed that the GO 10 wt% composite achieved the highest shielding effectiveness, with an average value of approximately 19.6 dB in the X-band frequency range (8–12 GHz), while ZnO-based composites exhibited moderate performance. Analysis of the shielding components indicated that absorption appears to be the dominant mechanism, with minimal contribution from reflection. This behavior suggests effective impedance matching and highlights the role of interfacial polarization and internal energy dissipation in attenuating electromagnetic waves. Practical EMF measurements further demonstrated a clear reduction in transmitted radiation, supporting the trends observed in VNA analysis, although these results are considered qualitative due to instrumental limitations. Overall, the results demonstrate that GO-reinforced benzoxazine/epoxy nanocomposites provide enhanced EMI shielding performance primarily governed by absorption mechanisms, highlighting their potential as lightweight EMI shielding materials.

Acknowledgment

The authors would like to acknowledge GADD, Kingdom of Saudi Arabia, for supporting this research through project number (GADD_2024_01_364).

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