

From atoms to macrostructures: Multiscale design and evolution of graphene-based electromagnetic wave absorbing materials

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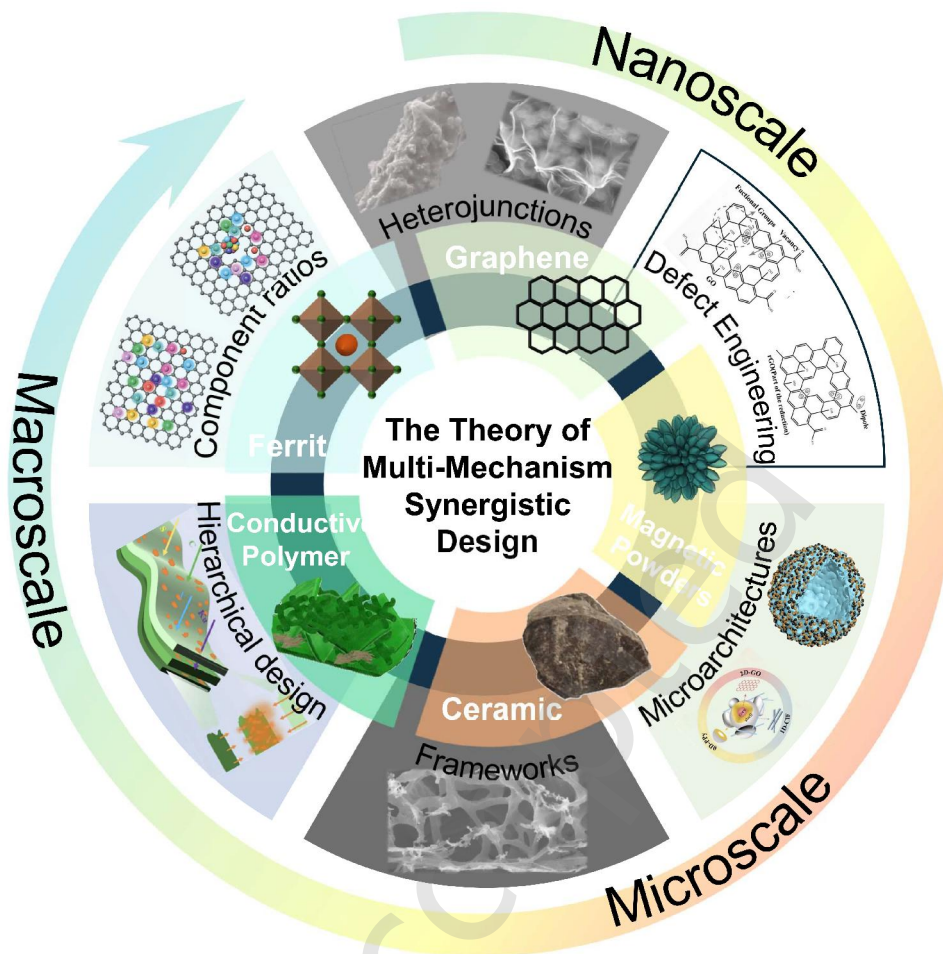
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This review comprehensively analyzes the evolution of graphene-based electromagnetic wave absorbing materials across a "Nano-Micro-Macro" framework, detailing how structural engineering, synergistic loss mechanisms, and multifunctional integration overcome traditional performance bottlenecks. Additionally, emerging multifunctional and intelligent systems are further discussed to guide the future development of adaptive electromagnetic materials.

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ABSTRACT: Electronic communication technologies have been widely utilized in both military and civilian sectors, giving rise to urgent concerns about electromagnetic pollution. Electromagnetic wave absorbing materials, capable of converting incident electromagnetic energy into alternative forms without reflection, offer a promising solution to this problem. Among the diverse classes of absorbers, graphene has attracted sustained attention owing to its atomic-scale thickness, large specific surface area, high carrier mobility, and unique two-dimensional conductive framework. The integration of graphene with complementary components not only diversifies energy-dissipation pathways and improves impedance matching, but enables the construction of tailored microstructures that extend electromagnetic propagation paths and enhance structural stability. This review summarizes recent advancements in graphene-based composite absorbers. Beginning with the fundamental design principles of electromagnetic wave absorbing materials, it elucidates the theory of synergistic, multimechanistic design and outlines the scientific rationale and structure-property relationships underlying composite architectures. Materials are categorized by component type, with discussion of their synthesis strategies, microstructural features, absorption mechanisms, and performance characteristics, alongside a critical comparison of their advantages and limitations. Finally, major challenges confronting the field are highlighted, and prospective research directions are proposed. It is expected to provide a roadmap for design and development of high-performance graphene-based electromagnetic wave absorbing materials for future applications.

KEYWORDS: graphene-based composites; electromagnetic wave absorption; multiscale synergistic design; structure-property relationships

1 Introduction

With the rapid advances in wireless communication, radar detection, aeronautical engineering and high-frequency electronics, electromagnetic waves (EMW) have become indispensable to information transmission, navigation, and target identification [1]. However, their ever-increasing prevalence has intensified the severity of electromagnetic pollution. Electromagnetic interference, on the one hand, interrupts the normal functioning of integrated circuits and compromises the stability of electronic systems. On the other hand, excessive exposure can have adverse effects on the human immune and nervous systems, as well as the growth and development of flora and fauna, rendering the mitigation of electromagnetic pollution an urgent necessity [2-4]. Moreover, as an essential counter-stealth technology, electromagnetic wave radar has been widely adopted worldwide. Its continuously improving detection capability poses mounting challenges to the survivability of advanced aerospace weaponry, elevating electromagnetic wave management and suppression into national security issues. Effective attenuation of electromagnetic radiation and

control of electromagnetic pollution are therefore critical scientific and technological imperatives [5, 6].

At present, two principal strategies are employed to suppress electromagnetic interference: reflection and absorption, corresponding to reflective materials and electromagnetic wave absorbing materials, respectively. Traditional reflective materials, however, are prone to generate secondary electromagnetic pollution due to their strong reflection of incident waves. By contrast, electromagnetic wave absorbers dissipate or attenuate electromagnetic energy by converting it into heat or other forms of energy, or by cancelling it out by interference, thereby achieving a substantial reduction in electromagnetic pollution. As a result, absorption-based approaches are now dominating the development landscape [7, 8]. Nevertheless, conventional absorbers, such as ferrites, magnetic metal powders, and silicon carbide, demonstrate effectiveness within certain frequency ranges. However, they commonly suffer from critical limitations, namely high density, large matching thickness, and narrow effective absorption bandwidth, which often fail to meet the demands of "thin, light, wide, and strong" absorption performance [9-11].

Compared with traditional absorbers, carbon-based materials offer significant advantages, including high electrical conductivity, large specific surface area, low density and excellent chemical stability, making them highly promising for electromagnetic-wave attenuation [12]. Recently, carbon allotropes with diverse dimensionalities have been actively explored as next-generation absorbing materials. Zero-dimensional carbon nanospheres, possess high surface areas and abundant surface termination sites, yet the charge transport between isolated nanospheres is often hindered by interparticle contact resistance [13]. One-dimensional carbon nanotubes, enable efficient axial electron transport, but their performance is frequently compromised by intertube junction resistance, entanglement, and aggregation, which obstruct the formation of continuous conductive networks [14]. Three-dimensional porous carbons feature low density and rich pore structures that facilitate geometric confinement of electromagnetic waves. However, their skeleton conductivity is generally inferior, and the structural tunability remains limited [15]. Additionally, conventional carbonaceous materials such as carbon black, carbon nanofibers, and amorphous carbon are attractive for their low cost and scalable production, although they typically exhibit disordered conductive networks and single energy-dissipation mechanisms, resulting in modest absorption performance [16].

Since the discovery of graphene in 2004, graphene-based materials stand out by simultaneously addressing the limitations of the aforementioned counterparts. Unlike zero-dimensional carbon nanospheres, atomically thin graphene sheets provide not only an ultrahigh specific surface area but also an intrinsic two-dimensional conductive network that facilitates charge delocalization without relying on interparticle contacts [17]. Compared with one-dimensional carbon nanotubes, graphene can more readily assemble into planar or three-dimensional percolated frameworks with tunable connectivity and impedance characteristics, thereby circumventing the dispersion and contact-resistance issues that plague tubular architectures [18]. Relative to three-dimensional porous carbons, graphene offers superior carrier mobility and versatile microstructural architectures, such as porous, hollow, core-shell, multilayered, and hierarchical structures, which can promote multiple internal reflections and extend electromagnetic propagation pathways without increasing material volume, thereby strengthening absorption performance [19]. Moreover, graphene exposes abundant interface sites for dipolar and interfacial polarization while maintaining exceptional electrical transport properties, enabling synergistic dielectric and conductive losses [20]. Nevertheless, pristine graphene absorbers often suffer from excessive conductivity, limited energy-dissipation mechanisms, and poor impedance matching, collectively restricting their absorption efficiency [21].

To overcome these limitations, increasing research efforts have been directed toward combining graphene with diverse complementary materials, including magnetic metal powders and metal oxides, to construct graphene-based composites with superior absorption capabilities. These

enhancements stem from the synergistic coexistence of dielectric and magnetic loss mechanisms, coupled with optimized impedance matching [22, 23]. This review systematically synthesizes recent developments in graphene-based composite electromagnetic wave absorbers. First, the performance evaluation systems of electromagnetic wave absorbing materials are outlined, accompanied by a concise introduction to the theory of multi-mechanism synergistic design. Subsequently, the recent progress of graphene as an individual electromagnetic wave absorber is summarized, laying out the scientific rationale for composite-material design and its structure-property relationships. Then we introduce the latest advances in graphene-based composite absorbers according to their constituent types, with emphasis on synthesis strategies, microstructural features, absorption performance, and material-specific advantages, and additionally summarize multifunctional integrated systems and intelligent-response materials. Finally, the key challenges confronting the field are outlined, and prospective research directions and technological trajectories are proposed.

2 Performance Evaluation Framework and Multi-Mechanism Synergistic Design Theory

2.1 Performance Evaluation Framework for Electromagnetic Wave Absorbing Materials

When electromagnetic waves impinge upon a material, three fundamental processes occur: surface reflection, internal absorption, and transmission [24]. Electromagnetic wave absorbers attenuate electromagnetic waves during internal propagation. After penetrating the material, the incident waves interact with molecular dipoles, charge carriers, and microstructural features, and their energy is dissipated through various electromagnetic loss pathways. These pathways convert electromagnetic energy into heat, mechanical vibration, or other dissipative forms, thereby reducing the transmitted and reflected wave intensities [25]. An ideal electromagnetic wave absorbing material should simultaneously permit maximal wave penetration through effective impedance matching and rapidly attenuate the incident radiation via strong intrinsic loss capability. These properties are quantitatively evaluated using the complex permittivity (ϵ' , ϵ'') and complex permeability (μ' , μ''). The real parts (ϵ' , μ') represent energy storage capacity, while the imaginary parts (ϵ'' , μ'') signify dielectric and magnetic loss abilities, respectively. The input impedance matching and reflection are calculated using the following transmission line theory equations (1)

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \left(\frac{2\pi f d}{c} \sqrt{\epsilon_r \mu_r} \right) \right] \quad (1)$$

$$RL = 20 \lg \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad (2)$$

Where f is the frequency, d is the absorber thickness, c is the velocity of light, and Z_0 is the impedance of free space. Excellent impedance matching is achieved when Z_{in}

approaches Z_0 , implying nearly zero surface reflection [24]. Electromagnetic wave absorption performance of materials is typically evaluated using two key parameters: minimum reflection loss ($RL_{\min}$) and effective absorption bandwidth (EAB). $RL_{\min}$ refers to the lowest reflection loss (Equations 2) observed across the entire frequency range at a given sample thickness, fundamentally reflecting both impedance matching and intrinsic energy-dissipation capability. Expressed in decibels (dB), a more negative value in $RL_{\min}$

indicates superior attenuation performance. EAB denotes the continuous frequency range in which $RL < -10$ dB at a given thickness, corresponding to the absorption of more than 90% of the incident electromagnetic energy. Expressed in gigahertz (GHz), a wider EAB implies broader operational bandwidth and greater applicability. Additionally, the attenuation constant (α) is often employed to evaluate the intrinsic dissipation intensity (Equations 3):

$$\alpha = \frac{\sqrt{2}\pi f}{c} \sqrt{(\mu''\epsilon'' - \mu'\epsilon') + \sqrt{(\mu''\epsilon'' - \mu'\epsilon')^2 + (\mu'\epsilon'' + \mu''\epsilon')^2}} \quad (3)$$

2.2 Classifications of Fundamental Electromagnetic Loss Mechanisms.

Based on the dominant loss mechanisms, electromagnetic wave absorbing materials can be categorized into three classes:

(a) **Conductive Loss Materials:** Characterized by a high dielectric loss tangent, these materials attenuate electromagnetic radiation through interaction with the electric field. When exposed to incident waves, such materials induce eddy currents, which in turn generate secondary magnetic fields, thereby converting electromagnetic energy into heat and dissipating it. Representative examples include low-resistance carbon-based materials (graphite, graphene, carbon nanotubes), conductive polymers, and nonmagnetic metallic powders [27].

(b) **Magnetic Loss Materials:** These materials attenuate electromagnetic waves primarily through mechanisms such as domain wall resonance, natural resonance, eddy current loss, and hysteresis loss. They are generally categorized into ferrites and metallic magnetic microparticles: ferrites are typically structured as spinel, garnet, or hexaferrite phases, whereas metallic magnetic absorbers include carbonyl-derived metal microparticles and fine metallic powders obtained via evaporation or reduction of organometallic precursors [28].

(c) **Dielectric Loss Materials:** Characterized by a high dielectric loss tangent, dielectric loss materials attenuate electromagnetic waves through polarization processes. Polarization loss spans electronic, ionic, dipolar, and

interfacial polarization mechanisms, which are active from optical/ultraviolet, infrared, microwave, and low-frequency to microwave regimes, respectively [29]. Because electronic and ionic polarizations respond only in the ultrahigh-frequency regime (103-106 GHz), dipolar and interfacial polarizations are the sole polarization contributors within the microwave band [30]. Under alternating external electromagnetic fields, molecular dipoles exhibit orientation lag while interfacial charges undergo displacement and accumulation, thereby consuming electromagnetic energy and converting it into thermal energy. Typical dielectric absorbers include barium titanate, silicon carbide, and silicon nitride [31].

These fundamental loss mechanisms are not isolated phenomena, but are activated and amplified at different structural length scales. Electronic and ionic polarization are primarily governed by atomic-scale chemistry and bonding configuration; dipolar relaxation and conductive loss are strongly influenced by molecular polarity, defect chemistry, carrier concentration, and local charge transport [32]; whereas interfacial polarization, multiple scattering, and impedance matching are typically engineered through nanoscale interfaces, microscale heterostructures, porous architectures, and hierarchical assembly [33]. Accordingly, the rational design of high-performance electromagnetic wave absorbers should integrate intrinsic dielectric/magnetic response regulation with multiscale structural construction, so that complementary loss channels can be synergistically activated across different length scales [34].

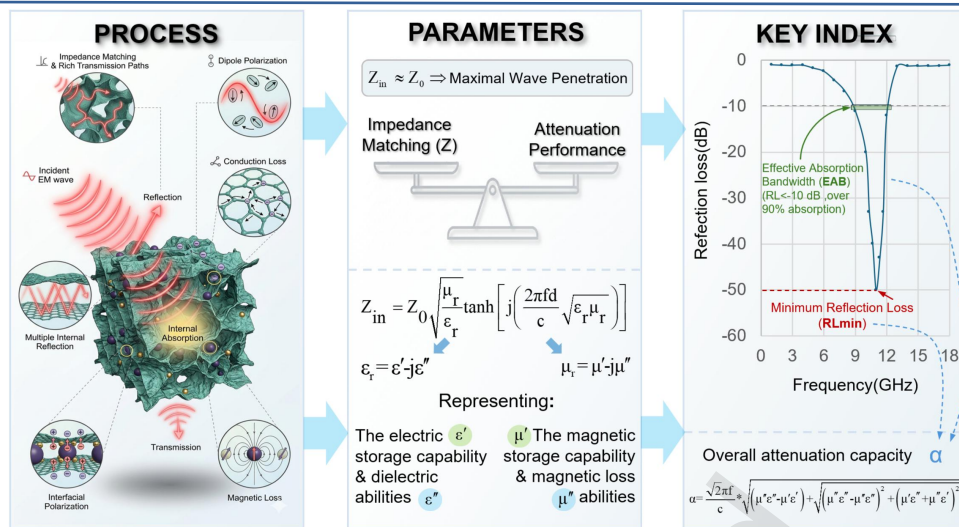


Figure 1 Flow Diagram for Evaluation of Microwave Absorption Performance

3 Unique Advantages, Single-component Progress and Inherent Limitations of Graphene

3.1 Intrinsic Advantages and Absorption Mechanisms of Graphene

Graphene, a monatomic carbon sheet composed of an sp^2 -hybridized honeycomb lattice, exhibits exceptional electrical, thermal, and mechanical attributes [35]. Its linear energy-band dispersion features the intersection of the valence and conduction bands at the Dirac point, where charge carriers behave as massless Dirac fermions with extraordinarily high mobilities ($>10^4 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$). This zero-bandgap nature fundamentally endows graphene with outstanding electrical conductivity [36]. Moreover, its conductivity can be continuously modulated across a broad range via electrostatic gating or heteroatom doping, offering versatile pathways to optimize impedance matching [37]. Under electromagnetic irradiation, the oscillation of intrinsic free carriers induces pronounced Ohmic dissipation, converting electromagnetic energy into thermal energy and thereby generating conductive losses. Concurrently, multiple polarization behaviors—including electronic, ionic, interfacial, and dipolar orientation polarization—occur within graphene layers and at heterogeneous interfaces, contributing to dielectric losses [38]. Notably, graphene's ultrahigh specific surface area ($>2600 \text{ m}^2 \cdot \text{g}^{-1}$) and inherent defect structures significantly enhance interfacial and dipolar polarization, imparting a high dielectric constant. Although intrinsically non-magnetic, graphene can acquire localized magnetic moments through structural defects, edge states, or heteroatom doping, thereby exhibiting a degree of magnetic responsiveness in the electromagnetic wave regime [39].

3.2 Experimental Progress of Single-Component Graphene Absorbers

In 2012, monolayer graphene was reported with a shielding efficiency of 2.27 dB within the 2.2–7 GHz frequency range, which was seven times higher than that of a gold film of the same thickness [40]. Multilayer graphene was then fabricated into films by sequential indirect stacking of monolayer sheets, where a four-layer graphene film exhibited a peak shielding effectiveness of 7.36 dB and an

average value of 5.83 dB in the 12–18 GHz band [41].

Nevertheless, 2D graphene possesses a relatively high complex permittivity, which complicates impedance matching. As a result, incident electromagnetic waves are more likely to be reflected than absorbed. To balance this trade-off and manipulate localized energy-transduction channels at the sub-micron scale, researchers have developed three regulatory methodologies:

(a) **Defect Engineering:** Defect engineering functions as the primary atomic-scale technique to deliberately manipulate the microscopic electromagnetic density of states, modifying the intrinsic energy dissipation pathways of graphene [42, 43]. For instance, Song et al. utilized a magnetic rotating arc plasma technique to inject nitrogen heteroatoms into the carbon lattice. By adjusting the input power to 13.5 kW, they precisely tuned the N-doping profile, creating permanent charge polarization centers that accelerated high-frequency dipolar relaxation to deliver an $RL_{\min}$ of -50.0 dB ($d = 3.1 \text{ mm}$) [44]. Chu et al. fabricated reduced graphene oxide (rGO) sheets via a modified Hummers method followed by high-temperature thermal treatment (Fig. 2a). When assembled into a three-layer configuration, the tailored density of localized residual functional groups acting as defect dipoles expanded the EAB to 11.5 GHz (6.5–18.0 GHz) [45]. Similarly, Large-area GO sheets with varying reduction levels were prepared to tune overlapping micro-conductive networks (Fig. 2b and 2c). Establishing abundant localized defect states that behave as dense polarization trapping sites allowed the absorber to reach a superior $RL_{\min}$ of -59.12 dB (EAB = 6.90 GHz) at a thickness of 4.04 mm and an ultra-low filler loading of 1.5 wt% [46].

(b) **Heterointerface Engineering:** In single-component systems, heterointerface engineering manifests as the macro-to-microscopic boundary alignment between stacked, misoriented, or segmented graphene nanosheets, creating localized electrical potential barriers to disrupt excessive conductivity [47]. Liu et al. compiled reduced graphene oxide paper (RGOP) via vacuum filtration. By systematically optimizing the lamination sheet number and interlayer thickness, they artificially generated a dense array of overlapping two-dimensional rGO/rGO sheet boundaries. These structural boundaries acted as localized potential

barriers that forced free carriers out of traditional long-range percolative conduction and into scattering-assisted hopping paths, successfully dampening excessive skin-layer conductivity to yield an $RL_{\min}$ of -26.5 dB at 10 GHz ($d = 4.92$ mm) [48]. As shown in Fig. 2d, 2e and 2f, Li et al. demonstrated a decoupled process of carbon deposition and in-situ $g-C_3N_4$ pyrolysis within a chemical vapor deposition (CVD) system to fabricate porous, N-doped graphene-like carbon nanosheets. The boundaries established between the

primary graphene domains and the in-situ derived nitrogenous carbon sub-phases created robust localized potential barriers. Under high-frequency EM fields, these junctions promoted intense quantum-tunnelling events and out-of-phase dipolar relaxation, converting wave energy into thermal dissipation to output an $RL_{\min}$ of -50.2 dB at a thin thickness of 2.0 mm (EAB = 5.9 GHz) [49].

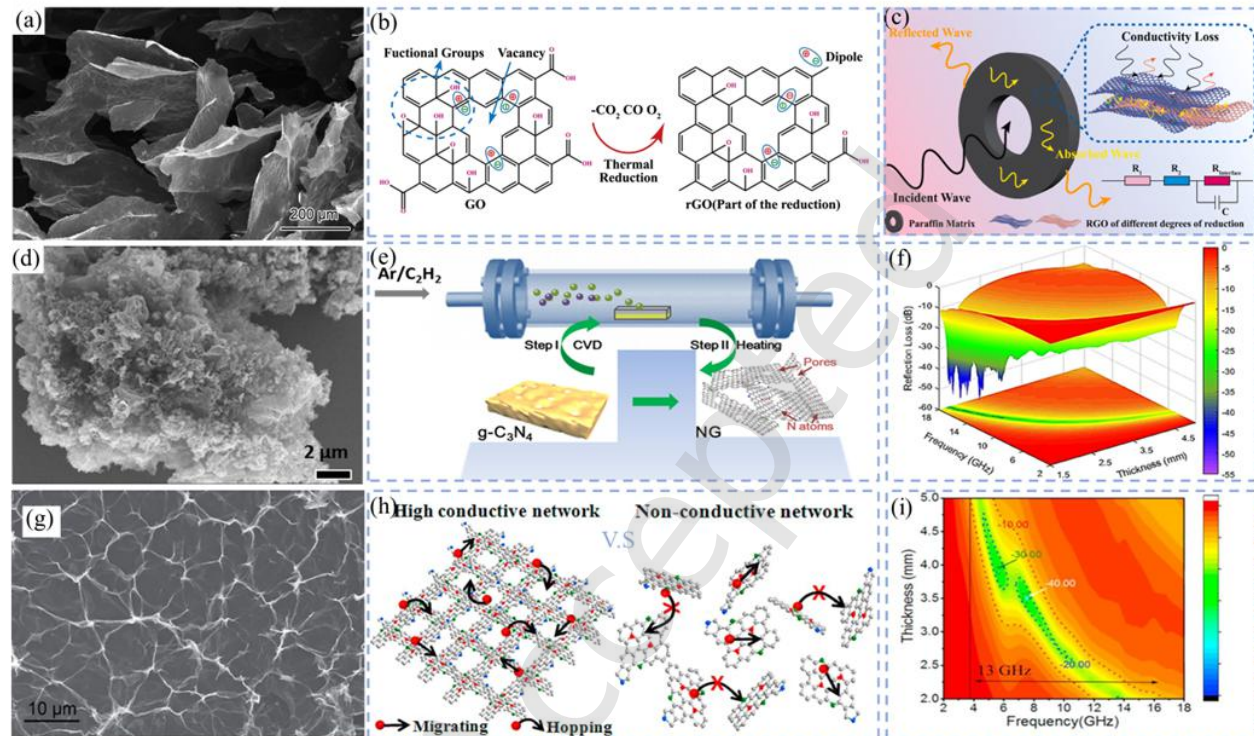


Figure 2 Graphene-Based Single-Component electromagnetic wave absorber. (a) SEM micrograph of rGO. Reproduced with permission from Ref. [45] © Beijing Institute of Aeronautical Materials 2025. (b) thermal reduction mechanism of GO and (c) schematic illustration for the electromagnetic microwave absorption mechanisms rGO composites. Reproduced with permission from Ref. [46] © Elsevier Ltd. 2022. (d) SEM micrograph of NG-800, (e) schematic illustration of the formation of N-doped graphene-like carbon nanosheets and (f) three-dimensional RL image of NG-800. Reproduced with permission from Ref. [49] © Elsevier B.V. 2020. (g) SEM micrograph of TRGN-1. Reproduced with permission from Ref. [51] © Royal Society of Chemistry 2015. (h) schematic illustration of electromagnetic wave absorption mechanism of N-doped graphene foams: high conductive network V.S non-conductive network and (i) RL image of NGF₈₀₀-0.6. Reproduced with permission from Ref. [52] © Elsevier B.V. 2019.

(c) Three-dimensional frameworks Engineering: Single-component engineering utilizes curved carbon shell layers, porous enclosures, and 3D geometric frameworks to emulate wave-trapping and decoupling behaviors within pure carbon boundaries [50]. Ultralight three-dimensional graphene networks (TRGN) were fabricated through thermally reducing graphene oxide/polyvinyl alcohol blends, followed by complete removal of the polymeric components to leave a pure carbon skeleton (Fig. 2g). The interconnected macroscopic skeleton served as a robust structural framework that physically eliminated the detrimental interlayer π - π stacking of graphene sheets, preserving a massive specific surface area. This spatial architecture successfully maintained a minimum filler loading of only 1 wt% while delivering a $RL_{\min}$ of -43.5 dB and an EAB of 7.47 GHz ($d = 3.5$ mm) [51]. Representing the optimized convergence of monocomponent strategies, Liu et al. fabricated ultralight N-doped graphene foams via a hydrothermal self-assembly route combined with freeze-

drying (Fig. 2h and 2i). The resulting open-network architecture formed curved carbon cell walls that acted as continuous geometric shells encapsulating low-permittivity air cores ($Z_{in} \approx Z_0$). This multi-shelled open topology forced entering EM waves into continuous cross-phase refraction, scattering, and extensive internal sub-reflections, vastly extending internal wave-trapping lifetimes. Simultaneously, the integration of localized N-doping nodes maximized polarization loss. With only 5 wt% filler loading, this unified single-phase absorber exhibited a remarkable $RL_{\min}$ of -53.9 dB and an exceptionally broad EAB of 13.0 GHz ($d = 3.5$ mm) [52].

3.3 Inherent Limitations of Single-Component Graphene Systems

Despite the commendable progress noted above, single-component pristine graphene and its derivatives still face several inherent limitations in practical applications. Graphene's high electrical conductivity, while beneficial for dissipating electromagnetic energy, simultaneously causes

the input impedance to deviate substantially from that of free space, resulting in pronounced surface reflection rather than absorption and severely reduced energy-coupling efficiency [53]. Moreover, graphene-based systems predominantly rely on conductive loss mechanisms and lack synergistic contributions from magnetic loss or interfacial polarization, leading to a singular attenuation pathway characterized by narrow absorption bandwidths and sharply localized peaks—insufficient for broadband electromagnetic wave attenuation. The ultrathin lamellar nature of graphene restricts the effective propagation path of incident electromagnetic waves; once the material is thickened by layer stacking, strong interlayer π - π interactions readily induce dense agglomeration, which enhances interfacial reflection and further weakens overall absorption performance. In addition, graphene sheets exhibit a strong tendency to aggregate and possess poor dispersibility, resulting in macroscopic structural inhomogeneity and diminished stability of their electromagnetic properties [54].

3.4. Conceptual Framework of Multiscale Synergistic Design

The severe impedance mismatch, narrow operational bandwidth, singular dissipation pathways, and structural instability inherent to monocomponent materials present fundamental bottlenecks that severely restrict their practical application in high-performance electromagnetic (EM) wave absorption. Breaking these intrinsic trade-offs requires a paradigm shift toward multi-component modification guided by the Theory of Multiscale Synergistic Design. By constructing hierarchical, multi-responsive architectures, this design framework integrates distinct energy-dissipation pathways to achieve multi-channel attenuation and optimized structure-property coupling.

To implement these foundational loss mechanisms systematically within practical matrices, the multi-mechanism balance must be deliberately engineered across a continuous spatial spectrum. Rather than operating as isolated dimensional boundaries, the three hierarchical length scales function as progressive strategic domains to

couple and harmonize conductive, dielectric, and magnetic attenuation pathways:

(a) **Nanoscale:** At the nanoscopic level, the primary objective centers on utilizing localized dielectric loss centers to actively disrupt and manipulate graphene's excessive conductive pathways, thereby optimizing impedance matching at the atomic source. The formation of heterojunctions at phase boundaries induces sharp discontinuities in carrier mobility, work function, and intrinsic conductivity, driving localized space-charge accumulation and widening the operational frequency range. Concurrently, atomic- or lattice-scale imperfections (such as vacancies, edge states, and heteroatom dopants) operate as active polarization centers that intensify defect-induced dipolar relaxation, while deliberate tailoring of the local electronic density of states (DOS) fine-tunes surface conductivity to prevent surface reflection [55]. By suppressing excessive free-carrier accumulation at the front interface, this atomic-scale engineering prevents severe skin-layer wave reflection and facilitates seamless electromagnetic wave penetration into the matrix interior.

(b) **Micro-Mesoscale:** At the micro-mesoscopic level, the focus shifts toward the structural arrangement of multiphase domains, aiming to integrate discrete magnetic and dielectric loss components while maximizing internal propagation pathways. Sophisticated architectures, such as core-shell configurations, hollow spheres, or 3D porous scaffolds, effectively coordinate the spatial distribution of distinct loss phases to enforce a balanced magneto-dielectric coupling condition. This structural coordination minimizes the disparity between the input impedance and free-space impedance ($Z_{in} \approx Z_0$), ensuring that incident waves cross the physical boundary with minimal interfacial reflection. Furthermore, these geometries expand internal wave-trapping lifetimes via continuous multiple scattering, simulate localized micro-scale capacitive domains, and physically eliminate the detrimental interlayer π - π stacking of graphene sheets, preserving structural reliability under extreme conditions [56, 57].

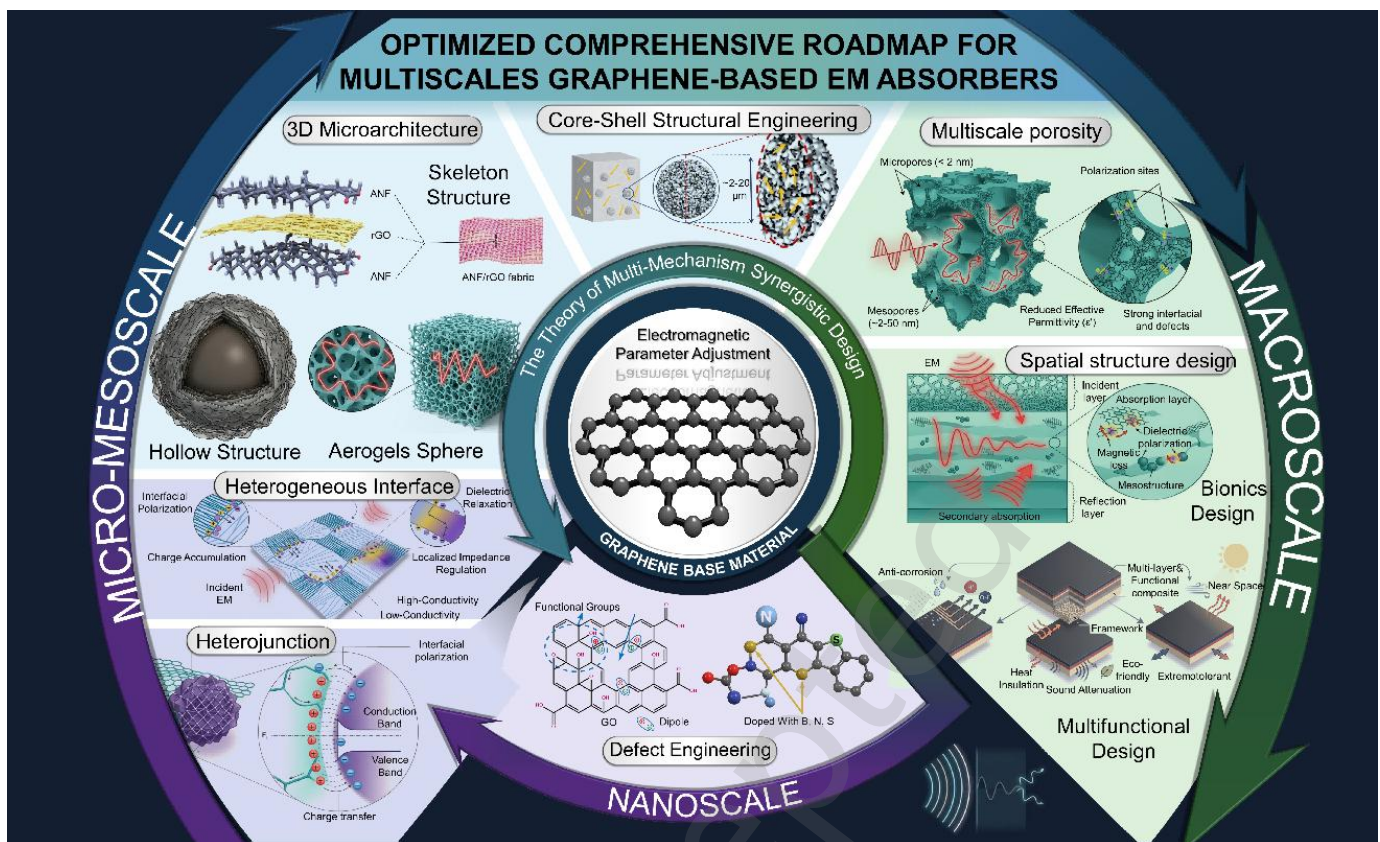


Figure 3 Multiscale Synergistic Design of Graphene-Based Composite Microwave Absorption Materials. Subsequent section (Section 3.4) systematically deconstructs these advanced binary and multi-phase heterostructures, analyzing how the strategic integration of diverse chemical phases into the graphene matrix bridges the permeability gap and actualizes the definitive multiscale synergistic design theory.

(c) Macroscale: At the macroscale, the overarching goal involves the global integration and synergistic balancing of all loss channels to produce multifunctional, lightweight, broadband absorbers. Advanced computational tools, including machine-learning models and genetic algorithms, are deployed to explore the vast composition space, identifying optimal loading levels locked near the percolation threshold. This spatial layout integrates intrinsic material properties with architectural functions, utilizing bio-inspired multilayer designs (e.g., "incident-absorption-reflection" tri-level systems) and multiscale porosity regulation. By incorporating low-permittivity air pockets ($\epsilon_{\text{air}} \approx 1$) within the macroscopic skeletal framework, the

bulk effective permittivity is strongly depressed, successfully mitigating the intrinsic impedance mismatch of dense graphene and matching the wave impedance of free space over a broader frequency spectrum. In addition, electromagnetic metamaterials represent another important strategy at the macroscale. Through the rational design of subwavelength artificial unit cells and periodic architectures, metamaterials enable precise regulation of effective electromagnetic parameters and wave propagation behaviors, thereby offering new opportunities for impedance matching, broadband absorption, and multifunctional electromagnetic wave management. [58].

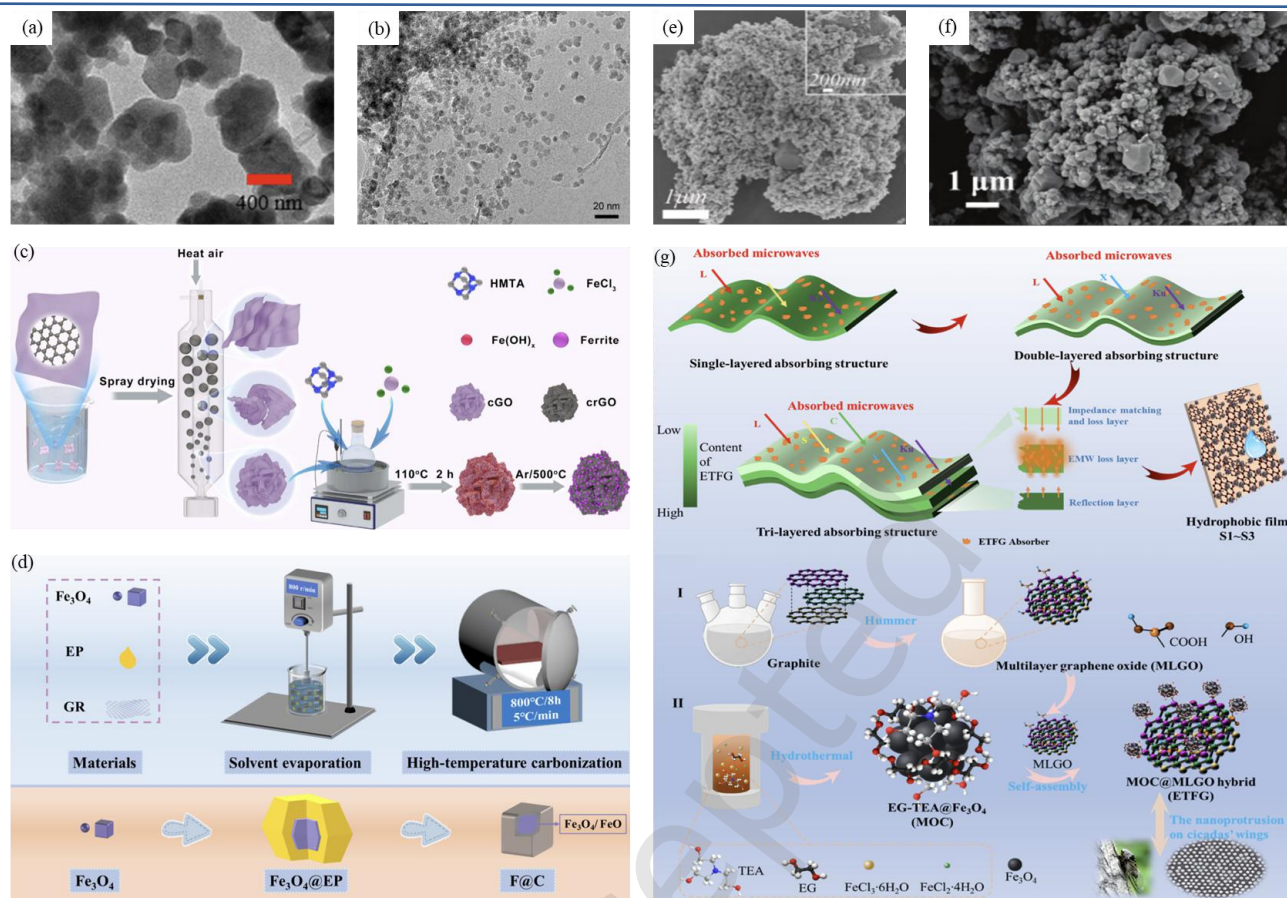


Figure 4 Graphene/Ferrite Binary Composite Electromagnetic Wave Absorbing Materials. (a) SEM image of Fe_3O_4 @rGO nanoparticles. Reproduced with permission from Ref. [62] © Qian et al. 2022. (b) TEM image of rGO/ Fe_3O_4 nanocomposite. Reproduced with permission from Ref. [63], © Yu et al. 2019. (c) Schematic illustration of the synthesis and (e) SEM image of Fe_3O_4 @crGO composites. Reproduced with permission from Ref. [64] © American Chemical Society 2025. (d) Flow chart of F@C composite material preparation and schematic diagram of core-shell structure formation and (f) SEM image. Reproduced with permission from Ref. [65] © John Wiley & Sons, Inc. 2025. (g) Schematic microstructure of layered absorbing structures and composite film with self-cleaning property. Reproduced with permission from Ref. [69] © Elsevier B.V. 2025.

4 Graphene-Based Binary Composite Electromagnetic Wave Absorbing Materials

4.1 Graphene/Ferrite

Ferrites, a class of ferromagnetic or ferrimagnetic oxides primarily composed of iron, typically adopt spinel or hexagonal crystal structures. As relatively mature magnetic loss materials, ferrites exhibit advantages such as high saturation magnetization, Snoek's limit frequency, and low production cost. Nevertheless, conventional ferrites encounter inherent limitations, including high density and a singular loss mechanism [59]. The integration of ferrites with graphene optimizes impedance matching by suppressing

graphene's high dielectric constant while inducing synergistic magneto-dielectric coupling through eddy-current loss, natural resonance, and dipolar polarization [60]. Furthermore, nanoscale ferrite particles tend to form stable three-dimensional hybrid microstructures with graphene and its derivatives. This architecture not only significantly increases the number of heterogeneous interfaces and strengthens interfacial polarization, but also prolongs the propagation pathways of electromagnetic waves and promotes a more homogeneous distribution of the

constituent phases [61].

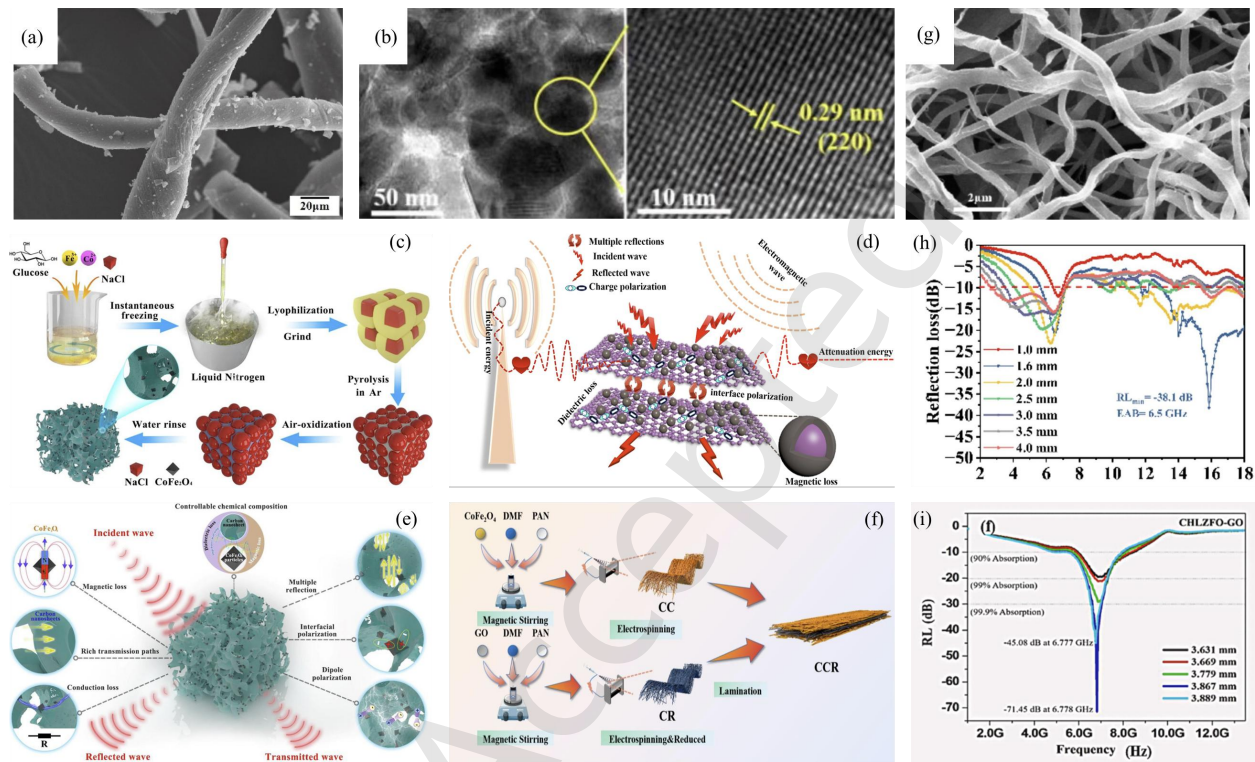
Early research focused on anchoring ferrite nanoparticles onto graphene sheets to create heterogeneous interfaces. For instance, Qian et al. employed a hydrothermal method under an external magnetic field to synthesize chain-like Fe_3O_4 @rGO nanocomposites (Fig. 4a). The material achieved an $\text{RL}_{\min}$ of -49.4 dB at 16.2 GHz with a thickness of 1.75 mm [62]. Yu et al. prepared Fe_3O_4 nanoparticles encapsulated within reduced graphene oxide via a one-step reaction (Fig. 4b). This system reached a superior RL of -55.71 dB at 6.78 GHz with a thickness of 3.5 mm, while at 1.7 mm, it provided an EAB of 4.76 GHz (13.24-18 GHz) [63]. As illustrated in Fig. 4c and 4e, Xu et al. constructed wrinkled, spherical rGO hybrids decorated with Fe_3O_4 nanocrystals, producing Fe_3O_4 @crGO composites with exceptional absorption properties. By tailoring thickness (2.5-5 mm), EAB spanned the entire C- and X-bands (4-12 GHz). At 4.5 mm, the material exhibited an $\text{RL}_{\min}$ of -52.3 dB at 5.4 GHz, accompanied by a 2.3 GHz EAB [64]. Wang et al. fabricated core-shell F@C composites through carbon-coating strategies (Fig. 4d and 4f). In this system, electron hopping was facilitated by graphene defects and oxygen functionalities, while magnetic coupling at the Fe_3O_4 /FeO heterointerfaces markedly intensified electromagnetic energy attenuation. At a thickness of 1.55 mm, the composite

demonstrated a remarkable RL of -55.54 dB at 15.12 GHz and an EAB of 4.8 GHz (13.2-18 GHz) [65].

With continued exploration, numerous metal oxides structurally analogous to Fe_3O_4 have been introduced into the electromagnetic wave absorption domain. Compared with Fe-based counterparts, these oxides not only exhibit superior thermal stability and corrosion resistance but offer tunable electromagnetic parameters, broader response frequencies, and more diverse loss mechanisms. As depicted in Fig. 5a and 5d, Zhao et al. fabricated a series of multi-

derived carbon composites via mechanical alloying (Fig. 5c). At a thickness of 2.55 mm, the NCF25 sample achieved an RL of -20.46 dB at 10.01 GHz [68].

Beyond microscale design, the construction of macroscopic 3D architectures has emerged as a superior strategy for enhancing binary performance. Inspired by natural architectures, Wu et al. employed a simple hydrothermal and self-assembly route to construct cicada-wing-like multilayer absorbers (Fig. 5g), where EG-TEA@ Fe_2O_3 nanobumps functioned as protrusions and



element core-shell magnetic nanoparticles integrated with layered graphene, denoted $\text{CoFe}_2\text{O}_4/\text{C}/\text{rGO}$ (CCR). At 2 mm thickness, the composite yielded an optimal RL of -52.5 dB, and at 1.7 mm, the EAB extended to 5.68 GHz (12.32-18 GHz) [66]. Jiang et al. successfully employed electrospinning to produce flexible $\text{rGO}/\text{CoFe}_2\text{O}_4$ bilayer carbon fiber composites (Fig. 5b and 5g). By adjusting the CoFe_2O_4 -to-rGO ratio to balance magnetic permeability and dielectric permittivity, the material demonstrated an RL of -38.1 dB and an EAB of 6.5 GHz (11.5-18 GHz) at 1.6 mm thickness [67]. Similarly, Manju et al. synthesized nickel ferrite/cotton-

multilayered graphene oxide (MLGO) served as the skeletal framework. At 4.81 mm thickness, this material achieved an RL of -68.49 dB, along with an exceptionally broad EAB spanning 17 GHz, from the L- to Ku-band. Moreover, the micro-protrusions on the film surface effectively entrapped air within the inter-groove cavities, forming an air cushion that enhanced surface hydrophobicity. This self-cleaning property, evidenced by a contact angle of 116° , further underscores the multifunctional potential of graphene/ferrite absorbers [69]

Figure 5 Graphene/ferrite-like binary electromagnetic wave absorbing materials. (a) TEM image and (d) Absorbing mechanism diagram of CFO. Reproduced with permission from Ref. [66] © Elsevier B.V. 2022. (b) SEM images and (f) Schematic diagram of CCR. Reproduced with permission from Ref. [67] © Elsevier Ltd. 2025. (c) SEM image of NCF25. Reproduced with permission from Ref. [68] © Elsevier Ltd. 2024. (e) Schematic illustration of the preparation procedures and (h) Schematic illustration of electromagnetic wave mechanism. Reproduced with permission from Ref. [70] Elsevier B.V. © 2022. (i) Reflection loss curves of CHLZFO-GO. Reproduced with permission from Ref. [71] © Elsevier B.V. 2025.

Table 1 summarizes the preparation methods, microstructure, and absorption properties of typical graphene/ferrite binary materials, illustrating the transition

from simple particulate decoration to complex 3D structural engineering.

Table 1 Graphene/ferrite-like binary electromagnetic wave absorbing materials

Materials	Preparation Method	Microstructure	Thickness (mm)	Filler Loading(%)	RL _{min} (dB)	EAB (GHz)
$\text{Ba}_2\text{Co}_2\text{Fe}_{12}\text{O}_{22}/\text{rGO}$ [72]	reduction	hexagonal plate	2.0	66.7	-45.25	4.75

BaFe ₁₂ O ₁₉ /Graphene [73]	combustion	porous	3.0	88.0	-58.00	-
CoFe ₂ O ₄ /rGO [74]	solvothermal	flower-like	2.1	10.0	-67.58	6.30
SrFe ₁₂ O ₁₉ /rGO [75]	hydrothermal	-	3.0	-	-34.80	5.70
CoFe ₂ O ₄ /rGO [76]	hydrothermal	flake	2.3	-	-47.90	5.00
NiFe ₂ O ₄ /rGO [77]	hydrothermal	sphere	5.0	50.0	-42.00	5.30
γ-Fe ₂ O ₃ /rGO [78]	solvothermal	sphere	2.5	-	-59.65	-
MnFe ₂ O ₄ /rGO [79]	hydrothermal	granular	3.0	-	-29.00	4.88
ZnFe ₂ O ₄ /rGO [80]	hydrothermal	-	1.6	79.6	-29.30	2.60
Li-Co/rGO [81]	thermal	granular	3.0	-	-46.80	6.80
Ni _{0.4} Zn _{0.4} Co _{0.2} Fe ₂ O ₄ /rGO [82]	mechanical mixing	-	1.9	-	-38.70	6.20
Ni _{0.7} Zn _{0.3} Fe ₂ O ₄ /rGO [83]	electrospinning conversion	fibers	2.0	-	-37.71	3.68
CoFe ₂ O ₄ /graphene [84]	vapor diffusion	rugby-like	2.0	-	-39.00	9.60
Fe ₃ O ₄ /rGO [85]	solvothermal	bowl-like	2.0	30	-24.00	-

4.2 Graphene/ Magnetic Metal Powders

Magnetic metal micropowders offer high magnetic permeability, strong electromagnetic loss capability, and broad frequency responsiveness. When uniformly dispersed within a graphene matrix, they establish magneto-dielectric hybrid systems that markedly enhance attenuation performance. Simultaneously, the lightweight nature of graphene enables the fabrication of absorbers that combine low density with high electromagnetic wave absorption efficiency [86, 87].

Among these materials, carbonyl iron powder is widely employed due to its high saturation magnetization and its scalable fabrication [88]. For instance, Yang et al. synthesized a novel carbonyl iron/carbon foam (CI/CF) magneto-dielectric composite with a three-dimensional network structure via carbonization and vacuum impregnation (Fig. 6b). Benefiting from structure-induced eddy current losses, the material maintained a stable EAB of over 8.32 GHz even at elevated temperatures (298-573 K) [89]. Beyond static composites, the integration of magnetic powders with graphene has paved the way for smart, reconfigurable absorbers. A notable advancement is the use of shape-memory polymers (SMP) to create stimulus-responsive structures. Yin et al. designed an origami-inspired composite absorber comprising flake-shaped carbonyl iron powder (FCIP) and reduced graphene oxide (rGO) (Fig. 6a and 6d). The absorption properties could be dynamically modulated by external magnetic and thermal fields. When a 3.40 mm thick planar origami structure was thermally activated to

recover its folded configuration, the material achieved an exceptionally broad EAB of 14.40 GHz (3.60-18.00 GHz) and an RL_{min} of -26.64 dB at 9.76 GHz [90].

Magnetic metal alloys, owing to their high electrical and magnetic conductivities, benefit from polycrystalline features, particle interactions, and the synergistic effects of dielectric and magnetic losses, thereby significantly improving absorption efficiency. However, their inherently high density, tendency toward agglomeration, and limited oxidation resistance compromise long-term stability. Hybridization with graphene can mitigate these drawbacks by enhancing dispersion, interfacial adhesion, and environmental stability [91, 92]. For example, Liu et al. developed FeNi alloy/graphene foam (FNGF) composites through a facile one-step hydrothermal method (Fig. 6c), systematically investigating the effects of FeNi concentration on electromagnetic wave absorption. The FeNi/GF-1 sample, at 2.09 mm thickness, exhibited an EAB of 6.24 GHz (11.76-18 GHz), while FeNi/GF-3 achieved a remarkable RL_{min} of -63.76 dB at 15.68 GHz with a thickness of 7.6 mm [93]. Guo et al. synthesized rGO@Ni-FeCo layered double hydroxide (LDH) composites with hierarchical heterostructures through electrostatic self-assembly, freeze-drying, and thermal annealing (Fig. 6e). The catalytic activity differences among metal particles induced diverse dielectric-electromagnetic interfaces, effectively enhancing interfacial polarization. As a result, the composite delivered an RL_{min} of -51.8 dB at 1.4 mm thickness, along with an EAB of 4.5 GHz [94].

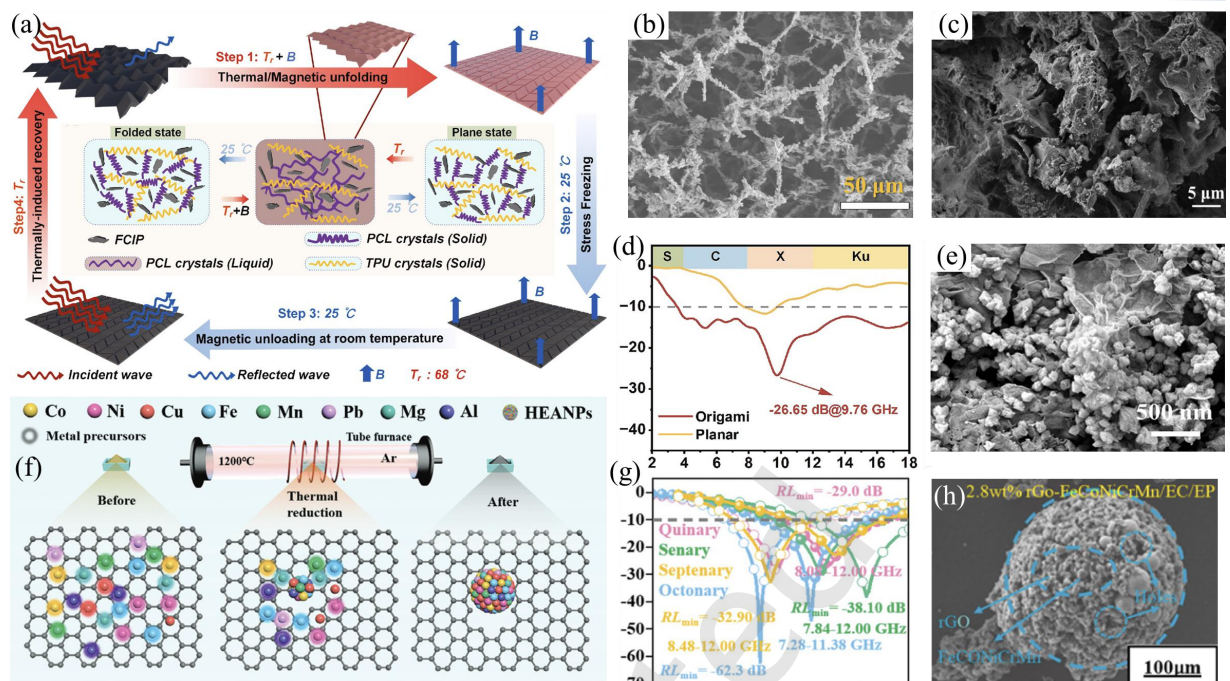


Figure 6 Graphene/magnetic metal powders binary electromagnetic wave absorbing materials. (a) Macroscopic deformation process of the absorber under thermal and magnetic field, along with a schematic diagram of electromagnetic wave absorption and reflection (outer) and Deformation mechanism at the microscopic level (inner) and (d) Experimental reflection loss curves of the origami-based absorber in the flat and folded state of origami-based electromagnetic wave absorber. Reproduced with permission from Ref. [90] © Elsevier B.V. 2025. (b) SEM image of CI/CF composites. Reproduced with permission from Ref. [89] © Elsevier Ltd. 2022. (c) SEM image of FeNi/GF. Reproduced with permission from Ref. [93] © Elsevier B.V. 2025. (e) SEM image of GO@Ni-FeCo LDH. Reproduced with permission from Ref. [94] © Elsevier B.V. 2025. (g) High-temperature sintering process of HEANPs/G composites and (f) RL and EAB across different frequencies of Quinary and Octonary HEANPs/G. Reproduced with permission from Ref. [95] © Wiley-VCH GmbH 2025. (h) SEM image of localized enlarged morphology of composite microspheres. Reproduced with permission from Ref. [96] © Elsevier Ltd. 2024.

A significant frontier in binary composites is the incorporation of High-Entropy Alloys (HEAs). Distinguished by high-entropy effect, lattice distortion, and sluggish diffusion dynamics, HEAs represent highly promising magnetic loss components [93]. For instance, He et al. fabricated hollow porous rGO-FeCoNiCrMn/EC/EP microspheres via a microemulsion method (Fig. 6h), where ethyl cellulose (EC) and epoxy (EP) resin served as the primary wall framework and core matrix, respectively. The resulting hollow porous morphology enhanced multiple electromagnetic wave reflections and scattering, thereby improving impedance matching. With 5.4 wt% rGO loading and a thickness of 2.5 mm, the composite achieved an $RL_{\min}$ of $-50.46\ \text{dB}$ at $10.08\ \text{GHz}$, while at 1.5 mm thickness it exhibited an EAB of 3.6 GHz (11.2–14.8 GHz) [96]. As depicted in Fig. 6f and 6g, Zhang et al. employed a thermochemical reduction strategy to synthesize HEA nanoparticle/graphene (HEANPs/G) composites. By increasing the alloy composition to eight elements, they intensified lattice distortion and heterogeneous charge distribution across interfaces, thereby reinforcing interfacial polarization losses to achieve a high $RL_{\min}$ of $-62.30\ \text{dB}$ (3.13 mm) and EAB of 4.16 GHz (2.60 mm) [95]. The integration of magnetic powders and graphene reaches its structural peak through three-dimensional (3D) printing technology. This additive manufacturing approach offers exceptional design flexibility, allowing for the precise construction of complex architectures that synergistically improve absorption across

microscopic and macroscopic scales [100]. For example, Gao et al. (Fig. 7a–7c) incorporated CB-CIP hollow microspheres into 3D-printed composites via solvent evaporation. By adjusting the CB content, the microstructural features and absorption performance were finely tuned, achieving an $RL_{\min}$ of $-47.34\ \text{dB}$ at $10.48\ \text{GHz}$ and an EAB of 4.56 GHz (11.44–16.64 GHz) at 2.5 mm thickness [97]. Sun et al. (Fig. 7d–7f) prepared core-shell GO@PPy/CIF composites through an in-situ oxidative polymerization method. At a GO@PPy:GO@PPy/CIF mass ratio of 15 wt% and 2.13 mm thickness, the absorber achieved an $RL_{\min}$ of $-53.67\ \text{dB}$ at $12.24\ \text{GHz}$ with an EAB of 2.56 GHz [98]. Ye et al. (Fig. 7g and 7h) synthesized rGO-CIP composite microspheres via solvent evaporation and incorporated them into PLA matrices. Through ball milling and melt extrusion, they fabricated 3D-printed composite absorbers. With 5.1 wt% rGO loading and 2.2 mm thickness, the material exhibited an $RL_{\min}$ of $-50.1\ \text{dB}$ and an EAB of 6.24 GHz [99]. These advancements demonstrate that 3D printing enables the transition from material synthesis to intelligent structural design.

It should also be noted that when magnetic metal alloys such as FeCo or Ni are coupled with highly conductive graphene, the resulting carbon-metal interfaces may create a galvanic environment. In humid or saline conditions, this interfacial coupling can accelerate galvanic corrosion of the magnetic core, leading to partial oxidation or phase transformation into non-magnetic oxides and thereby compromising the magnetic loss contribution and long-term

stability of the absorber.

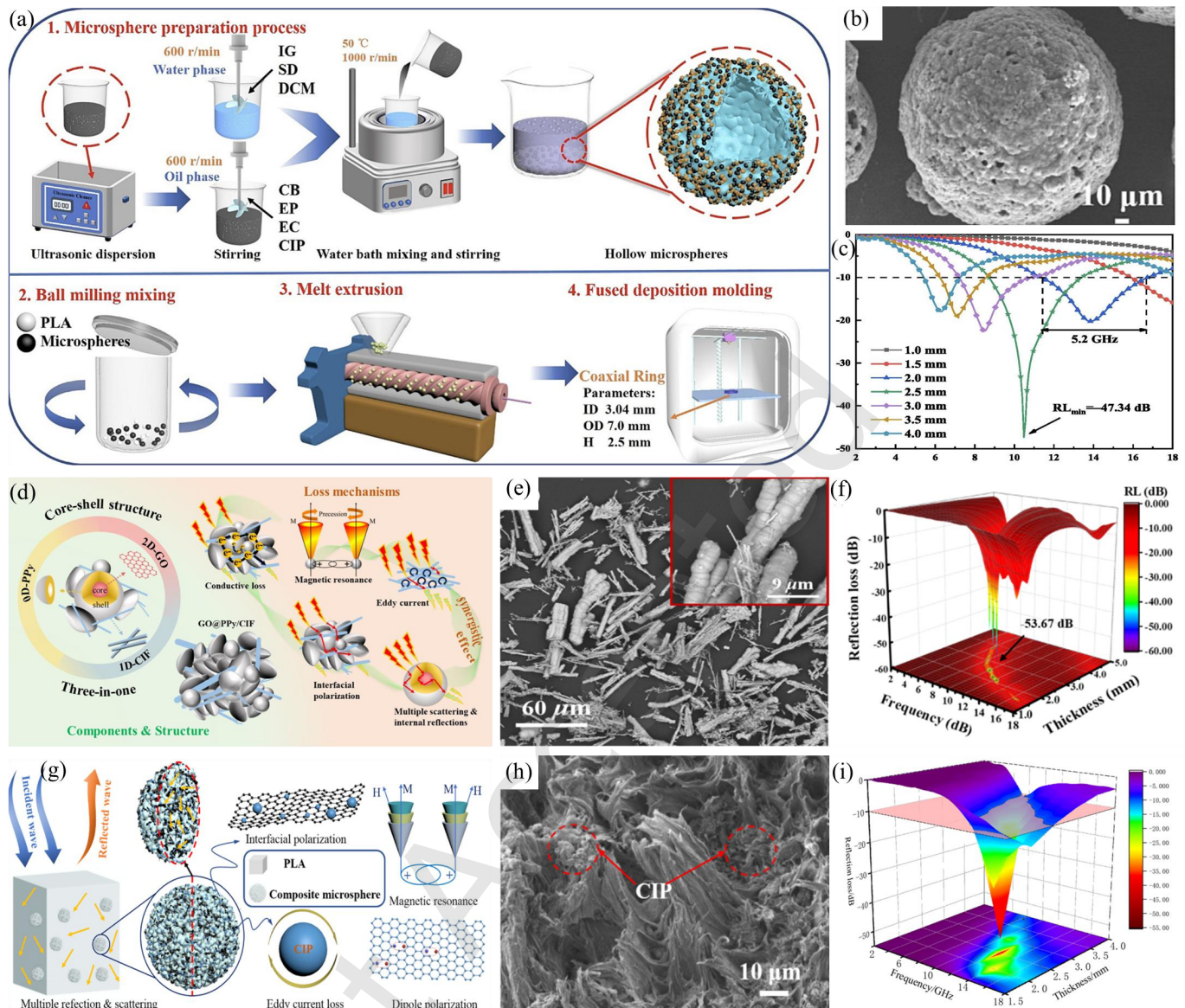


Figure 7 3D-printed graphene/magnetic metal powder binary electromagnetic wave absorbing materials. (a) Preparation process of CB-CIP porous hollow microsphere composites and (b) SEM image and (c) RL curves of CB-CIP. Reproduced with permission from Ref. [97] © Elsevier B.V. 2024. (d) The schematic diagram, (e) SEM image of pure CIFs, and (f) Reflection loss curves and 3D plots of reflection loss of GO@PPy/CIF composites. Reproduced with permission from Ref. [98] © Elsevier B.V. 2023. (g) Schematic diagram of electromagnetic wave absorption mechanism, (h) SEM images of composite wire cross-section, and (i) Reflection loss curves and 3D plots of reflection loss of rGO-CIP/PLA composites. Reproduced with permission from Ref. [99] © Elsevier B.V. 2023

4.3 Graphene/Conductive Polymer

Conductive polymers represent a class of electromagnetic wave absorbing materials that integrate the mechanical flexibility of polymer matrices with intrinsic electrical conductivity. Polymers such as polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh) have garnered significant attention for electromagnetic absorption applications [101]. However, pristine conductive polymers suffer from thermal instability, conductivity decay, and rapid performance deterioration. Hybridization with graphene provides an effective strategy to enrich energy dissipation pathways and enhance long-term durability [102, 103]. For instance, Liu et al. (Fig. 8a and 8b) employed graphene oxide (GO) as a structural template and synthesized sandwich-like PANI-GO-PANI composites via a one-step intercalative

polymerization of aniline under varied stirring durations. The composite achieved a $RL_{\min}$ of -28.12 dB at 5.675 GHz with a thickness of 5.5 mm, while tunable thicknesses between 2.5 and 5.5 mm yielded an ultrawide EAB of 13.175 GHz (4.825-18 GHz) [104].

Plant-derived extracts represent ideal carbon precursors, as they not only reduce energy consumption and production costs but also provide an environmentally benign and sustainable route for the fabrication of carbon-based absorbing materials. For example, Wu et al. (Fig. 8d) designed a bio-inspired absorber by depositing GO/PANI layers on bamboo powder (BP) substrates through interfacial polymerization, producing GO/PANI/BP composites. At 30 wt% filler content, the material achieved an RL of -44 dB at 9.36 GHz (3 mm thickness), while a

reduced thickness of 2 mm delivered an EAB of 5.36 GHz (12.64–18 GHz) [105]. Tang et al. (Fig. 8c and 8i) fabricated aramid nanofiber-reinforced reduced graphene oxide (ANF/rGO) fabrics via wet-spinning and subsequent chemical reduction, followed by in-situ doped polymerization of PANI to obtain ANF/rGO-PANI textiles. With a thickness of 2.9 mm, the composite exhibited an optimal RL of -52.3 dB at 12.27 GHz and an EAB of 6 GHz (12–18 GHz) [106].

In situ polymerization on graphene substrates is a critical technique that ensures uniform dispersion and strong interfacial adhesion, enabling integrated structure-function design [107]. For instance, Zhang et al. (Fig. 8e and 8h) prepared PPy/GO composites with varying ratios and reduction degrees via in-situ polymerization and thermal reduction. RT4-10 sample reached an RL of -66.64 dB and an EAB of 6.74 GHz at 2.43 mm thickness and 7.5 wt% filler loading, whereas the RT0-05 sample achieved an extraordinary RL of -72.65 dB at 4.40 mm thickness [108]. Furthermore, Zhang et al. (Fig. 8f and 8g) synthesized graphene nanosheet-PEDOT (GNS-PEDOT) nanofibers by in-situ polymerization, whereby PEDOT nanofibers were anchored onto graphene surfaces. At 2.0 mm thickness, the composite attained an $RL_{\min}$ of -48.1 dB at 10.5 GHz, with a broad EAB of 9.4 GHz spanning 5.8–12.3 and 12.9–15.8 GHz at thicknesses between 1.5 and 3 mm [109].

Moving beyond functional polymers like PANI and PPy, recent research has pivoted toward integrating graphene with high-performance engineering plastics. Among these,

polyimide (PI) stands out due to its imide-ring structure, which confers exceptional mechanical strength, corrosion resistance, and thermal stability across extreme temperatures (-269–1400 °C). Furthermore, its relatively low dielectric constant favors impedance matching [110]. The construction of 3D porous networks, such as aerogels and foams, is an effective strategy to amplify the performance of these binary systems. These architectures promote interfacial heterogeneity and strengthen coupling effects. As shown in Fig. 9a, 9b, 9c and 9f, Ji et al. fabricated a compressible polyimide/reduced graphene oxide composite aerogel (PGA) via freeze-drying and thermal annealing. The compressible aerogel enabled modulation of pore architecture and conductive pathways, thereby achieving dynamic tunability of electromagnetic parameters. At a thickness of 3.9 mm, the PGA demonstrated a remarkable RL of -58.32 dB and an EAB of 7.98 GHz (10.02–18.00 GHz) [111]. Li et al. synthesized graphene/polyimide composite aerogels (GPIs) through a one-pot solvothermal strategy, followed by thermal treatment at 350 °C to yield GPI350 (Fig. 9d and 9e). The optimized sample exhibited an $RL_{\min}$ of -75.90 dB at a thickness of 3.75 mm, while at 2.70 mm, the EAB reached 6.44 GHz [112]. Similarly, Zhou et al. developed polyimide-derived carbon foams (CPIFs) through microsphere foaming and carbonization (Fig. 9g and 9h). By tuning the pre-foaming and carbonization temperatures, both morphology and conductivity were adjusted. The optimized sample, PIF-650-3, delivered an EAB of 14 GHz and an $RL_{\min}$ of -46.8 dB at the thickness of 30 mm [113].

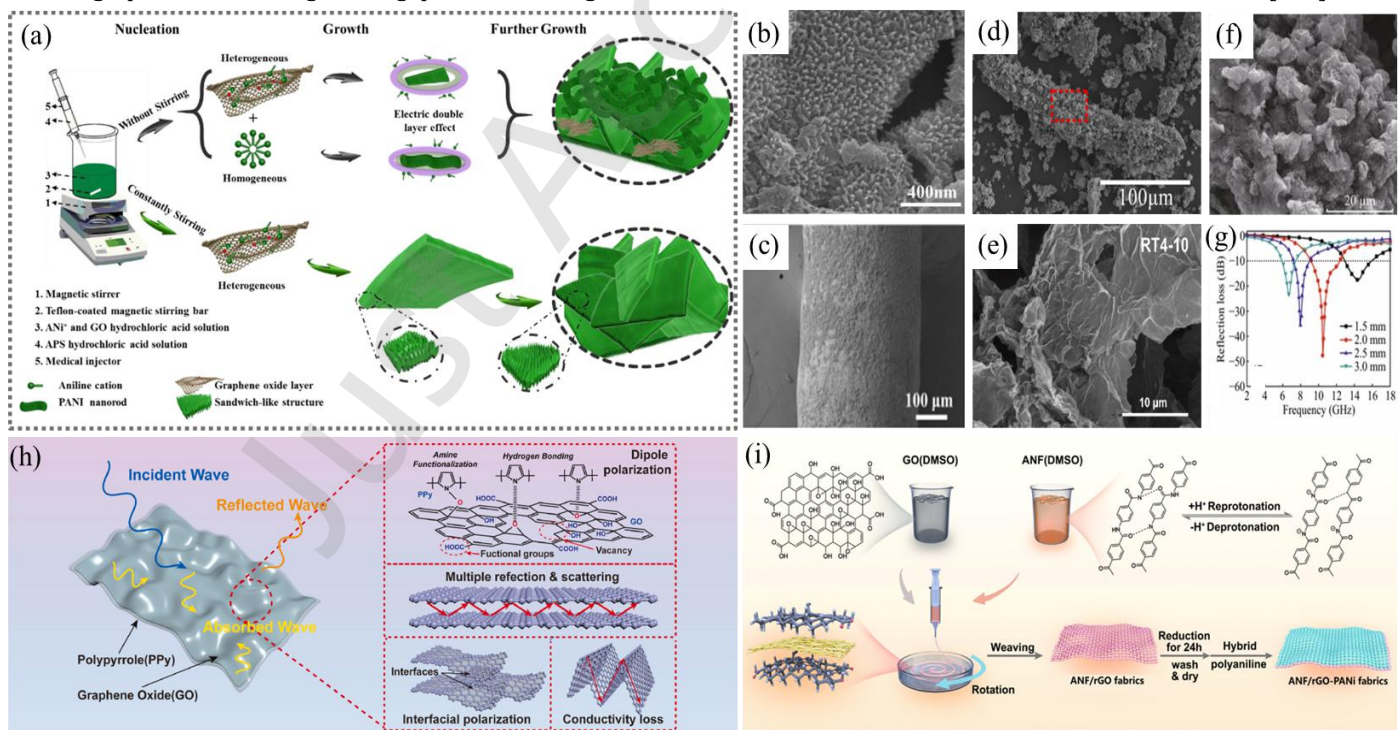


Figure 8 Graphene/conductive polymer binary electromagnetic wave absorbing materials. (a) mechanism of mechanical agitation inducing the formation and (b) SEM image of PANI-GO-PANI. Reproduced with permission from Ref. [104] © Elsevier B.V. 2019. (c) SEM images of ANF/rGO_{0.3}-PANI_{0.9} and (i) Synthesis process of flexible electromagnetic wave absorbing fabrics. Reproduced with permission from Ref. [106] © Taylor & Francis Ltd. 2024. (d) SEM images of GO/PANI/BP. Reproduced with permission from Ref. [105] © Elsevier B.V. 2024. (e) SEM image and (h) Schematic for the EMA mechanisms of PPy/GO. Reproduced with permission from Ref. [108] © Elsevier B.V. 2024. (f) SEM image and (g) Reflection loss curves of GNS-PEDOT. Reproduced with permission from Ref. [109] © Springer Nature 2016.

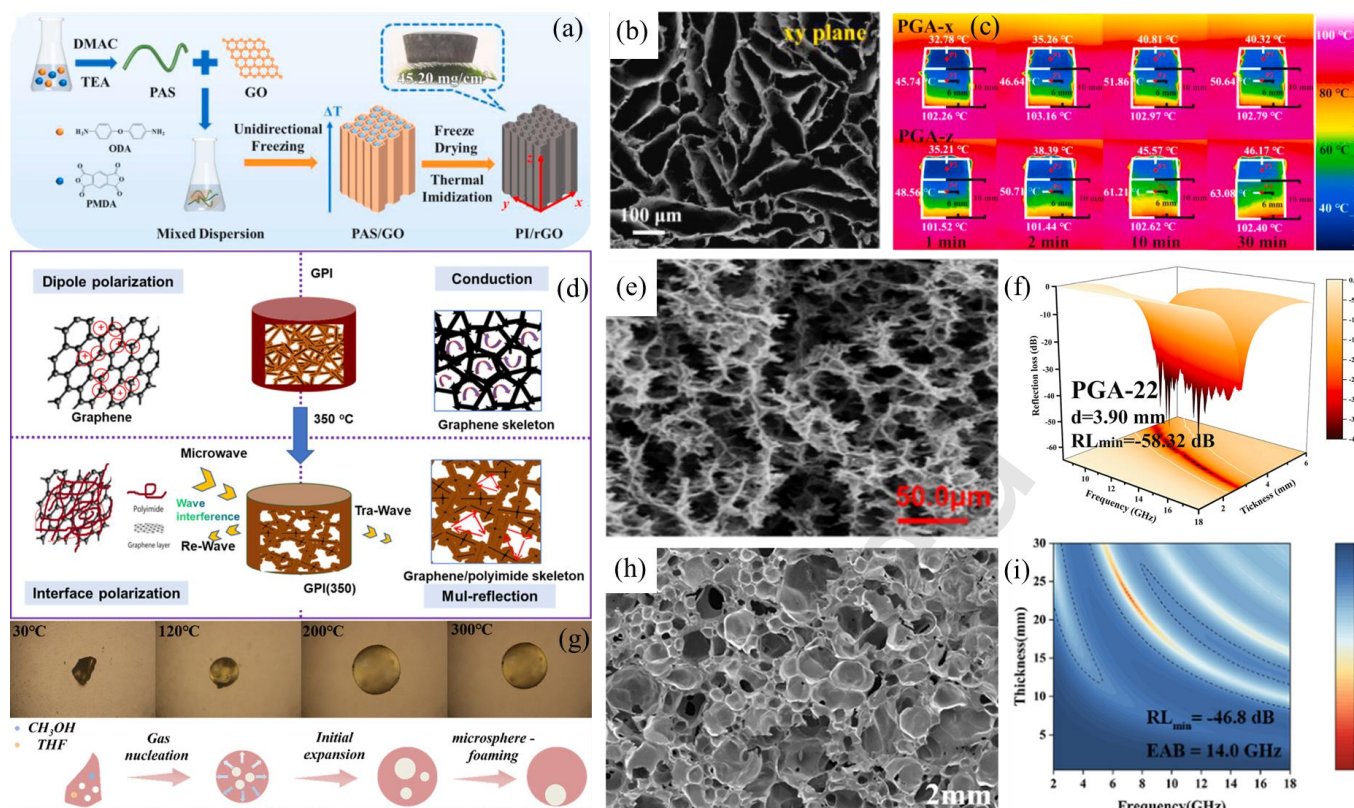


Figure 9 Graphene/polyimide binary electromagnetic wave absorbing materials. (a) Schematic illustration of the fabrication process, (b) SEM images, (c) Infrared thermal images, and (f) 3D RL plots of PGA composite aerogels. Reproduced with permission from Ref. [111] © Elsevier B.V. 2025. (d) Scheme of electromagnetic wave absorption mechanism for the GPI hybrid aerogel and (e) its SEM images. Reproduced with permission from Ref. [112] © American Chemical Society 2024. (g) Microscopic morphology of the PEA0 at different temperatures and (h) SEM image and 2D MA images of PIF-650-3. Reproduced with permission from Ref. [113] © American Chemical Society 2024.

The strategic integration of graphene has also been extended to other advanced engineering polymers. For instance, Chen et al. employed a phase inversion method to fabricate graphene nanoplate/polyethersulfone (GNP/PES) composites. Within the porous PES framework, GNPs constructed a unique three-dimensional conductive network that significantly enhanced electromagnetic wave absorption. The composite achieved an RL of -50.90 dB at 10.99 GHz with a thickness of 8.7 mm. Notably, even with only 5 vol% GNP dispersed along the pore walls, the composite retained a compressive strength exceeding 15 MPa, while also exhibiting favorable flame-retardant and thermal-insulating properties [114]. Comparable graphene-based composites have been reported with other advanced engineering polymers such as polycarbonate (PC) [115], polyetherimide (PEI) [116], and polyether ether ketone (PEEK) [117]. This paradigm shift—from simple electromagnetic attenuation to multifunctional, structure-function integrated materials—represents the current frontier of graphene/polymer binary absorbers.

Overall, the electromagnetic attenuation performance of graphene/conductive polymer composites is determined by a coordinated balance among conductivity, interfacial polarization, and impedance matching. In particular, material structure critically regulates impedance matching by modulating graphene loading and dispersion, porosity, thickness, and layered or hierarchical architectures, which

together adjust the effective permittivity and the interaction of incident waves with internal interfaces. Rational structural design can therefore avoid excessive conductivity while promoting multiple reflections and interfacial polarization, thereby enhancing energy dissipation.

4.4 Graphene/Ceramic

Ceramic materials represent a critical category of wave absorbers due to their high strength, thermal stability, oxidation resistance, and tunable dielectric properties. While ferrites have been extensively discussed as a class of magnetic ceramics in Section 4.1, this part will cover the broader ceramic systems including oxides, carbides, and nitrides [118]. Hybridization with graphene effectively reduces the characteristic high density and brittleness of ceramics while protecting the carbonaceous phase from oxidation, fulfilling the modern requirements for "thin, lightweight, broadband, and strong" absorbers [119].

Oxide-based ceramics remain foundational in this field. As illustrated in Fig. 10a and 10e, Jiao et al. achieved in situ growth of edge-rich graphene on alumina (Al_2O_3 /ERG), constructing composites with ultrahigh flexural strength and fracture toughness. At a thickness of 2 mm, the S5 sample exhibited RL values consistently below -7 dB in the X-band, with an EAB of 3.7 GHz [120]. Liu et al. converted vinyl-bridged GO/polycarbosilane precursors into rGO/SiC fibers (Fig. 10b and 10i). At a thickness of 3.0 mm, the optimized fibers delivered an RL of -42.6 dB, demonstrating the

effectiveness of solvent-free melt-blending in creating high-performance ceramic [121].

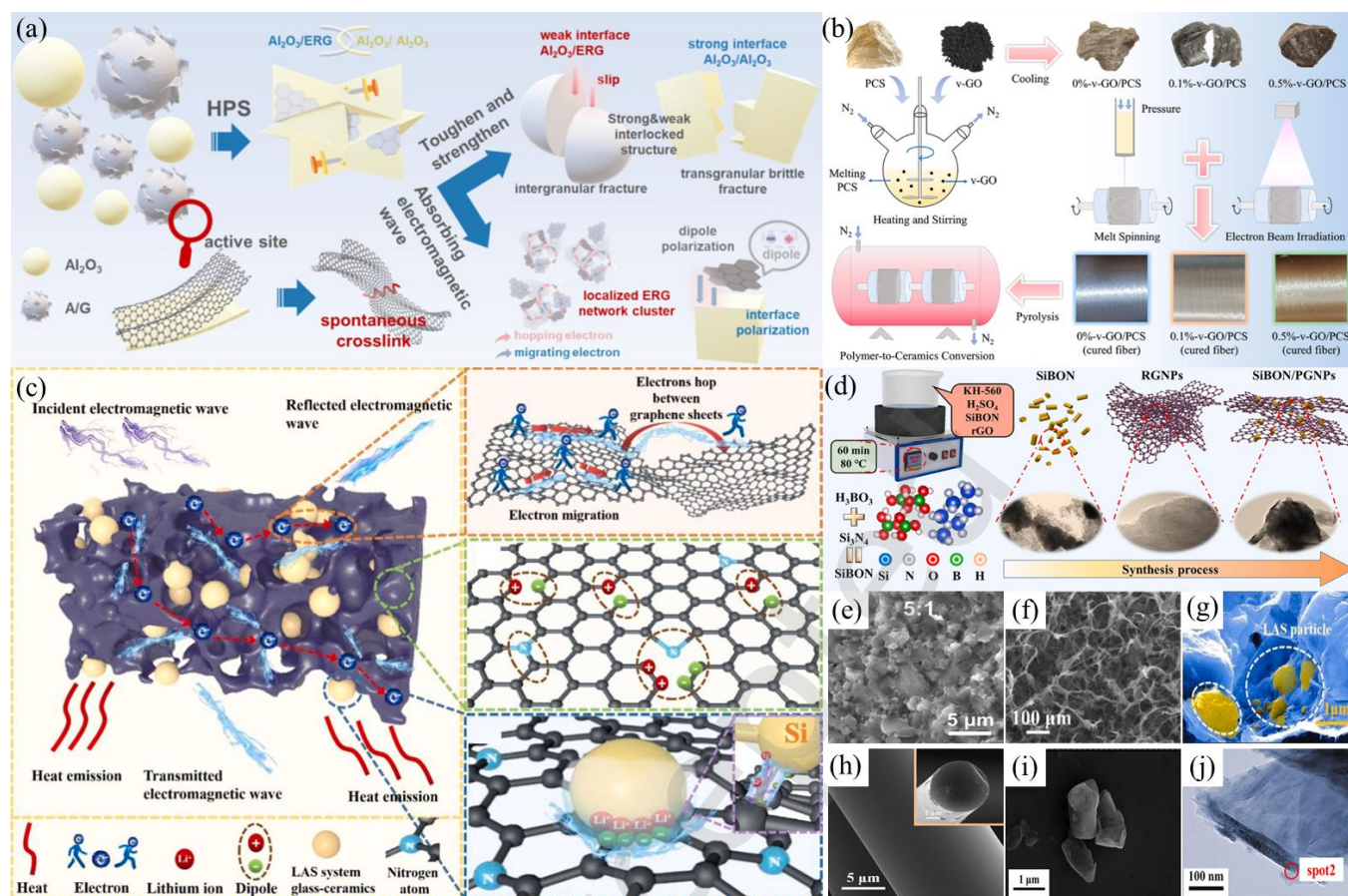


Figure 10 Graphene/ceramic binary composite electromagnetic wave absorbing materials. (a) Mechanism of mechanics and MA properties for crosslinked ERG doping Al_2O_3 composite ceramics and (e) Three-point bending crack morphologies of S5. Reproduced with permission from Ref. [120] © Elsevier B.V. 2025. (b) Preparation process diagram and SEM image of rGO/SiC fibers. Reproduced with permission from Ref. [121] © Elsevier B.V. 2025. (c) The absorption mechanism and (g) SEM image of LAS/N-GF. Reproduced with permission from Ref. [123] © Elsevier Ltd. 2025. (j) SEM image of b-13. Reproduced with permission from Ref. [124] © Elsevier B.V. 2025. (f) SEM image of SiO_2/rGO . Reproduced with permission from Ref. [122] © American Chemical Society 2024. (d) Reaction mechanism and (k) TEM image of RGNPs-SiBON. Reproduced with permission from Ref. [125] © Elsevier Ltd. 2023.

The aerogel strategy is particularly potent for graphene/ceramic composites. Because silicon-based ceramics provide a stable skeletal framework, they can effectively suppress the restacking and agglomeration of graphene sheets, enhancing both mechanical resilience and electromagnetic service life. For instance, Tian et al. fabricated ultralight silica nanofiber ceramic/reduced graphene oxide aerogels (SiO_2/rGO) via freeze-drying and carbonization (Fig. 10f). The ceramic nanofibers effectively inhibited graphene agglomeration, imparting excellent compressibility and fatigue resistance. The composite achieved an $\text{RL}_{\min}$ of -74.5 dB at 1.8 mm and an EAB of 5.7 GHz at 2.1 mm [122]. Similarly, Qi et al. prepared lithium aluminosilicate glass-ceramic/nitrogen-doped graphene aerogels (LAS/N-GF) through hydrothermal treatment and freeze-drying (Fig. 10c and 10g). With a filler content of 10 wt% and a thickness of 4.5 mm, the composite attained an RL of -47.98 dB at 8.96 GHz and an EAB of 8.34 GHz [123].

In addition to conventional ceramic matrices such as Al_2O_3 and SiO_2 , emerging ceramics have also been introduced into the design of advanced composite electromagnetic wave absorbers. Silicon boron oxynitride ceramics (SiBON)

represent a novel class of quaternary amorphous/nanocrystalline “structure-function integrated” materials, derived from the Si-O-N system with the strategic incorporation of boron. These ceramics synergistically combine the dielectric transparency of SiO_2 , the thermal stability of BN, and the mechanical robustness of Si_3N_4 , rendering them highly promising candidates for electromagnetic wave absorption [126]. For instance, Zhang et al. synthesized a series of low-dielectric SiBON ceramics by precisely tuning the boric acid content, and subsequently integrated them with reduced graphene nanosheets (RGNSSs) to fabricate SiBON/RGNSSs composites (Fig. 10j). By modulating the boric acid concentration, the dielectric response and thereby the absorption properties could be effectively tailored. Specifically, the b-12 sample achieved an EAB of 4.94 GHz at a thickness of 1.5 mm, while the b-13 sample delivered an $\text{RL}_{\min}$ of -50.45 dB at 16.16 GHz [124]. Li et al. developed SiBON/RGNPs composites via an innovative chemical grafting strategy (Fig. 10d and 10k). During SiBON formation, the (110) crystal planes of SiO_2 preferentially oriented and anchored at the edges of RGNPs, resulting in a unique composite architecture wherein SiBON acted as an

external antenna pole and RGNPs functioned as internal signal processors. When the SiBON-to-RGNPs mass ratio was 1:10 with a 20 wt% filler content, the composite exhibited an EAB of 4.80 GHz (12.88-17.68 GHz). Furthermore, at a mass ratio of 1:40 and a thickness of 1.7 mm, an RL of -50.43 dB was achieved at 13.44 GHz [125].

Overall, graphene/ceramic composites are distinguished by the intrinsic thermal stability, oxidation resistance, and mechanical robustness of ceramic matrices, which make them especially suitable for high-temperature and harsh-environment operation. In these systems, the ceramic framework provides the structural foundation for impedance matching, while pore architecture, graphene modification and dispersion, interfacial engineering, and hierarchical assembly collectively tailor the effective electromagnetic parameters and facilitate the penetration of incident electromagnetic waves into the absorber. Proper structural tailoring can thus preserve a low-reflection surface while sustaining sufficient internal attenuation, enabling ceramic-based absorbers to couple environmental durability with reliable electromagnetic wave dissipation. The development of graphene-based binary composite electromagnetic wave absorbing materials has evolved from simple composition optimization to sophisticated cross-scale structural engineering. By integrating graphene with ferrites, magnetic metal powders, conductive polymers, or ceramics, researchers have successfully established magneto-dielectric synergistic systems that overcome the impedance mismatch and narrow absorption bandwidth inherent in single-component materials.

5 Graphene-Based Multicomponent Composite Electromagnetic Wave Absorbing Materials

While binary composites significantly improve performance by pairing graphene with a second phase, they often face a trade-off between high attenuation and ideal impedance matching. To break these limitations, researchers have moved toward multicomponent systems. The introduction of a third functional component provides an effective route to further decouple conductivity regulation, polarization enhancement, and magnetic response tailoring. Such ternary architectures are conceptually distinct from binary systems because the additional component can be used to fine-tune the dielectric constant, create more heterogeneous interfaces, and broaden the range of accessible loss pathways, thereby improving impedance matching while preserving sufficient attenuation capability. In practice, structural factors such as component distribution, hierarchical porosity, interfacial density, and layered or core-shell arrangements directly determine how incident waves are coupled into the material and how the effective permittivity is balanced against free-space impedance. The multicomponent composites leverage a "synergy of three", where magnetic, dielectric, and conductive losses are precisely balanced to achieve superior reflection loss and ultra-wide effective absorption bandwidth. Therefore, this section extends the binary design paradigm toward more integrated multicomponent systems, where synergistic

interactions among multiple constituents enable more precise control over impedance matching and electromagnetic energy dissipation [127, 128].

Ternary systems allow for the simultaneous optimization of multiple decay pathways. Building upon binary foundations, these materials typically incorporate a carbon-based framework, a magnetic component, and a conductive polymer or ceramic coating. The integration of diverse morphologies-such as nanotubes, nanosheets, and polymers-creates a comprehensive micro-network for energy dissipation. For instance, Tian et al. fabricated multi-walled carbon nanotube (MWCNT)/reduced graphene oxide (rGO)/polypyrrole (PPy) ternary composites via an in-situ polymerization approach under hydrothermal conditions. In this system, MWCNTs and rGO nanosheets intertwine to form a relatively uniform micro-network, while PPy homogeneously coats the MWCNT/rGO substrate. The tunable loading of PPy optimized impedance matching and electromagnetic attenuation. The composite achieved an EAB of 4.6 GHz (13.4-18 GHz) at a thickness of 2.1 mm, with an RL_{min} of -57 dB at 15.8 GHz [129]. Similarly, Zhang et al. employed chemical vapor infiltration (CVI) to develop a hierarchical hybrid composite consisting of a porous three-dimensional rGO framework and layered boron nitride (BN)/silicon carbide (SiC) coatings. At a thickness of 2.9 mm, the composite achieved an RL of -37.8 dB at 9.02 GHz, while at 2.8 mm thickness, an EAB of 5.90 GHz was realized (7.88-11.76 GHz, 14.24-16.26 GHz) [130].

Rational spatial arrangement can further extend the propagation paths of incident waves and increase the density of heterogeneous interfaces. For instance, as illustrated in Fig. 11a and 11c, Hai et al. fabricated a sandwich-structured shielding composite (FePA/LIG) by employing laser-induced graphene (LIG) as the top and bottom layers, while utilizing co-precipitated Fe_3O_4 nanoparticles and in situ polymerized polyaniline (FePA) as the middle layer. The FePA850 sample exhibited an optimal RL of -53.96 dB at 9.36 GHz with a thickness of 3 mm, and an effective EAB of 4.86 GHz (13.14-18.00 GHz) at a thickness of 1.9 mm. Moreover, owing to the reflective effect of the LIG basal layer, the transmission of electromagnetic waves was nearly eliminated [131]. Shi et al. designed a ternary lightweight composite, SC@MnO₂/rGO (SCMR), by integrating MnO₂ nanosheets and two-dimensional reduced graphene oxide onto hollow submerged carbon nanoparticles (SC) (Fig. 11d). The SCMR composite achieved a maximum RL of -60.95 dB at 13.12 GHz with a matching thickness of 1.47 mm, and an EAB of 4.08 GHz (13.76-17.84 GHz) at 1.23 mm [132]. Dong et al. developed rGO nanosheets decorated with hollow core-shell Fe_3O_4 @PPy microspheres via a combination of hydrothermal synthesis, in situ polymerization, directional freeze-drying, and hydrazine vapor reduction (Fig. 11e and 11f). This composite reached an optimal RL of -61.20 dB at a thickness of 1.89 mm, and an EAB of 5.26 GHz at 1.71 mm [133].

To further optimize the intrinsic properties of the carbon matrix, Nitrogen-doped rGO (NRGO) has been widely integrated into ternary systems. Beyond increasing carrier concentration and elevating the Fermi level for better impedance matching, nitrogen doping introduces localized polarization centers and provides coordination sites (e.g.

pyridinic-N) that improve the dispersion of transition metal components [134].

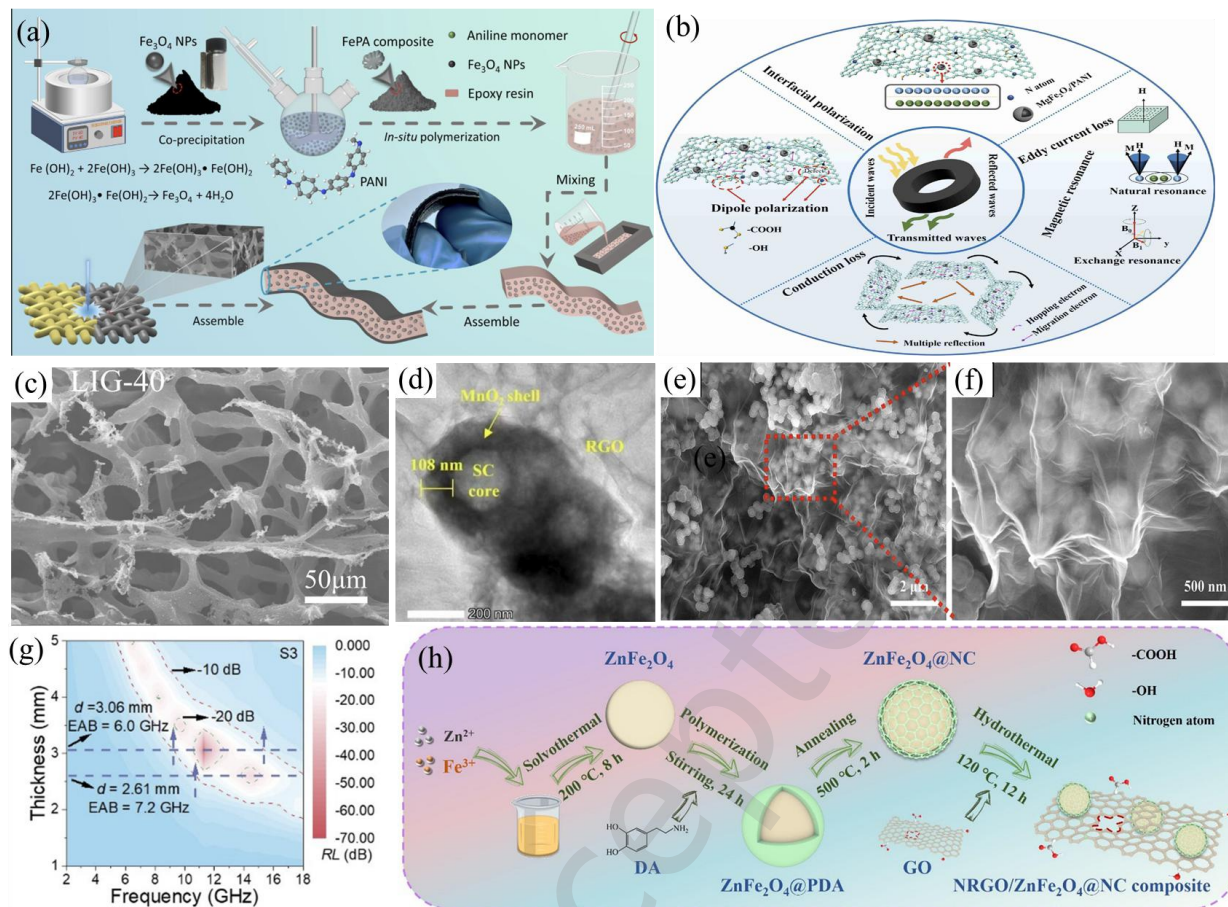


Figure 11 Graphene-based ternary composite electromagnetic wave absorbing materials. (a) Schematic of the fabrication process and (c) SEM image of FePA/LIG. Reproduced with permission from Ref. [131] © Elsevier B.V. 2023. (d) TEM image of SCMR. Reproduced with permission from Ref. [132] © Elsevier B.V. 2024. (b) Schematic diagram of electromagnetic wave absorption mechanism of NRGO/MgFe₂O₄/PANI composite aerogel. Reproduced with permission from Ref. [135] © Elsevier B.V. 2024. (e) (f) SEM image of FPG-4. Reproduced with permission from Ref. [133] © Elsevier B.V. 2023. (g) RL contour maps and (h) Schematic preparation process of NRGO/ZnFe₂O₄@NC. Reproduced with permission from Ref. [136] © Elsevier B.V. 2025.

For example, Shu et al. fabricated NRGO/MgFe₂O₄/PANI ternary aerogel coatings (Fig. 11b) through a three-step route involving solvothermal synthesis, in situ oxidative polymerization, and hydrothermal self-assembly. The thin PANI coating on MgFe₂O₄ and the core-shell MgFe₂O₄ structure synergistically enhanced absorption. At 3.57 mm thickness, the composite exhibited an optimal RL of -42.9 dB, while at 2.1 mm thickness, the maximum EAB reached 7.0 GHz (11.0-18.0 GHz) [135]. Furthermore, as shown in Fig. 11g and 11h, Shu et al. constructed NRGO/ZnFe₂O₄@NC ternary composites with abundant heterogeneous interfaces and unique core-shell architectures via a combination of solvothermal synthesis, in situ polymerization, annealing, and subsequent hydrothermal treatment. The ZnFe₂O₄@NC microspheres enhanced both dielectric and magnetic losses, while interfacial polarization was strengthened by the

heterogeneous boundaries. With 16.5 wt.% NRGO/ZnFe₂O₄@NC, the composite achieved a maximum RL of -61.1 dB at 7.2 GHz, and a maximum EAB of 7.2 GHz (10.8-18.0 GHz) at 2.61 mm thickness [136]. Advancing toward atomic-scale disorder, Ma et al. introduced dual N and S doping into graphene combined with MOF-derived Fe/Fe₂O₃/C/N. The incorporation of N and S atoms induced lattice defects and disorder while significantly enhancing interfacial and dipolar polarization mechanisms. The N, S-GPE composite attained an RL of -62.8 dB at 7.6 GHz with a thickness of 3.09 mm [137]. Table 2 summarizes the preparation methods, microstructure, performance of some typical graphene-based ternary composite electromagnetic wave absorbing materials, illustrating how the integration of three distinct phases pushes absorption boundaries.

Table 2 Graphene-based ternary composite electromagnetic wave absorbing materials

Materials	Preparation Method	Microstructure	Thickness (mm)	Filler Loading (%)	RL _{min} (dB)	EAB (GHz)
ZnFe ₂ O ₄ /PANI/rGO [138]	in-situ polymerization	core-shell	5.00	-	-39.80	5.50
GO/PANI/CB [139]	in-situ polymerization	agglomerates	2.00	-	-49.83	4.72
BaFe ₁₂ O ₁₉ /graphene/PANI [140]	cast coating	rich wrinkles	1.20	-	-37.36	5.40

Co-N/C/graphene [141]	hydrothermal and freeze-drying	rhombic dodecahedra	-	20.00	-46.80	5.30
SiC(rGO, Ni ₂ Si)Ni ₄ % [142]	re-pyrolysis	flake	2.00	4.00	-25.38	4.00
rGO@Co/Fe _{81.5} Si ₃ B ₉ P ₃ C ₁ Cu ₁ Ti _{1.5} [143]	alcoholthermal	lamellar	-	1.00	-52.41	6.07
NiZnFe ₂ O ₄ @MnO ₂ /GA [144]	hydrothermal and freeze-drying	core-shell	1.60	25.00	-55.78	3.52
ZnO/ZnFe ₂ O ₄ /rGO [145]	carbonization and hydrothermal	truncated octahedral	3.40	15.00	-61.60	26.78
ZnO@Fe ₃ O ₄ @rGO [146]	hydrothermal and annealing	spindle flower	2.50	70.00	-57.91	4.24
rGO/Fe ₃ O ₄ /AlN [147]	one-pot solvothermal	spherical-like	1.80	15.38	-59.39	5.68
S-Gr/CoNi/C [148]	hydrothermal and pyrolysis	granular	5.00	-	-47.7	-
Fe ₃ O ₄ /GNP/PLA [149]	melt mixing	granular	3.00	10.00	-37.00	2.90
Mo ₄ /3CT _x MXene/Graphene [150]	freeze-drying	lamellar	2.10	5.00	-37.00	4.20
CNT/MXene/F-rGO [151]	one-pot method	porous	2.50	25.00	-57.60	3.30
Graphene@MXene@Fe ₃ O ₄ [152]	screen-printing	porous	1.50	-	-47.60	3.50
Graphene/Mn-Zn ferrite/PLA [153]	ball-mill mixing and melt extrusion	flake-like	2.50	20.00	-24.30	5.12
(CoCrFeMnNi) ₃ O ₄ @C-Graphene/PLA [154]	powder static net melt molding technology	dual-core-shell	2.22	20.00	-51.36	5.20

6 Graphene-Based Composites for Multifunctional and Intelligent Applications

Binary and ternary graphene composites have yielded numerous materials with outstanding electromagnetic wave absorption performance; however, practical deployment requires materials to maintain performance in complex and variable service environments [155, 156]. As application scenarios diversify, the demand has shifted from singular EM attenuation toward multifunctional integration and intelligent responsiveness.

6.1 Environmental Adaptation: Corrosion Resistance and Durability.

In practical deployment, graphene-based absorbers must maintain high electromagnetic (EM) attenuation under complex and hostile conditions. In high-salinity or high-humidity environments, materials often encounter electrolyte infiltration, anodic dissolution, and structural degradation, which can compromise both EM performance and long-term durability. While hierarchical porous architectures provide superior energy dissipation, their high surface area often increases environmental sensitivity. Consequently, researchers have pursued diverse strategies to construct protective barriers without sacrificing absorption efficiency [157].

A primary strategy involves the encapsulation of sensitive magnetic components within stable carbonaceous shells to create a passivated interfacial barrier. Hou et al. fabricated a magnetic graphene composite aerogel (rGO/porous-hollow Ni/C microspheres, PHNiC) via self-assembly of PHNiC and graphene oxide followed by chemical reduction and freeze-drying. At a thickness of 2.5 mm, the composite achieved a $RL_{\min}$ of -51.3 dB with an EAB of 6.64 GHz. The conformal encapsulation of magnetic nanoparticles within rGO created a passivated interfacial barrier that effectively suppressed electrolyte penetration and anodic dissolution. After

corrosion testing, both the real and imaginary parts of the dielectric constant remained essentially unchanged, showing only minor fluctuations in the mid- and high-frequency regions, demonstrating excellent anticorrosion stability [158]. Beyond individual particle protection, the design of macroscopic networks can significantly delay the diffusion of corrosive ions. Xu et al. prepared 2D carbon sheets anchored with uniformly distributed hard/soft magnetic phases Fe₃C/ZnFe₂O₄/C. The FZC-1 sample attained a $RL_{\min}$ of -65.6 dB at a thickness of 4.02 mm and an EAB of 4.56 GHz at 2.26 mm. Benefiting from a “maze effect,” the interconnected carbon sheets elongated the diffusion pathways of corrosive ions, forming an efficient shielding network. After immersion in 3.5 wt.% NaCl solution for one month, the sample exhibited no visible corrosion or discoloration, underscoring its potential for long-term service in marine environments [159]. For extreme scenarios involving both chemical and thermal stress, the integration of 2D/3D heterostructures is essential. Zhan et al. developed a multifunctional 2D/3D rGO/CFs van der Waals hybrid through a simplified sequence of freeze-drying, soaking-absorption, secondary freeze-drying, and subsequent carbonization. This composite not only achieved an EAB of 6.2 GHz but also displayed excellent hydrophobicity and thermal-barrier performance, effectively suppressing thermal radiation while resisting strong chemical corrosion [160].

6.2 Structural-Functional Integration: Green and Daily-Use Applications

In the realm of daily electromagnetic shielding, absorber materials are shifting from a singular focus on electromagnetic wave attenuation towards an integrated approach that encompasses green, safe, and multifunctional properties. These materials must not only efficiently attenuate electromagnetic waves but also possess synergistic capabilities such as sound insulation, thermal insulation, and flame resistance, while maintaining environmental

friendliness, renewability, and biodegradability, thereby enabling structural-functional integration [165]. Meng et al. successfully synthesized a multidimensional heterostructure of multifunctional modified reduced graphene oxide/FeCo layered double hydroxide/polypyrrole (rGO/LDH/PPy) coating fabric via thermal reduction and in situ growth. The RL reached -45.0 dB at a thickness of 3.5 mm, and the material covered the entire X-band (2.5-5.5 mm) for EAB, with exceptional superhydrophobicity (Fig. 12a), self-cleaning performance, and excellent thermal insulation and flame retardancy [161].

Zhang et al. synthesized a hollow multiphase cobalt sulfide nanosphere (CoS , Co_9S_8 , Co_3S_4)/rGO aerogel with sulfur vacancies and heterogeneous interfaces via solvent heating, freeze-drying, and carbonization processes. The abundant sulfur vacancies and interface heterogeneity enhanced dipolar and interfacial polarization, achieving a RL of -33.4 dB and an EAB of 6.16 GHz at a thickness of 2.8 mm. The unique microstructure, particularly the three-dimensional porous network composed of periodic large pore units, effectively hindered heat conduction and convective pathways, resulting in excellent thermal insulation properties. Moreover, the material exhibited good electrochemical reversibility, maintaining 78.95% capacitance retention and near 100% Coulombic efficiency

after 5000 charge/discharge cycles at $10.0 \text{ A}\cdot\text{g}^{-1}$ (Fig. 12b) [162]. Jiang et al. used a directional freeze-drying strategy to integrate reduced graphene oxide / bacterial cellulose (rGO/BC) aerogel into hexagonal cavities of an aramid honeycomb substrate (GCH), creating a multifunctional GCH composite. The sample GCH-7 achieved full Ku-band (12-18 GHz) coverage of 12.1 GHz EAB, alongside superior fatigue resistance, heat insulation, self-extinguishing properties, and high-frequency sound absorption. After 100 compression cycles, it retained 87% of its initial compressive strength and structural integrity, and the material protected the flammable aramid honeycomb from combustion for 60 seconds under flame exposure (Fig. 12c). At a thickness of 20 mm, the sound absorption coefficient exceeded 0.4 in the 0.9-6.4 kHz range [163]. Gu et al. employed heterointerface engineering to design and synthesize a multifunctional lightweight rGO/polyimide hybrid aerogel. The sample S3 demonstrated -48.86 dB RL and an EAB of 10.19 GHz (12.33-22.52 GHz) at 3.6 mm thickness. At 75°C , it exhibited a low thermal conductivity of $0.037 \text{ W m}^{-1} \text{ K}^{-1}$ (Fig. 12f), and the material also possessed excellent soundproofing properties, achieving a maximum sound absorption coefficient of 0.457 at a low frequency of 63 Hz, benefiting from a unique acoustic resonance drum structure and a three-dimensional porous network (Fig. 12d) [164].

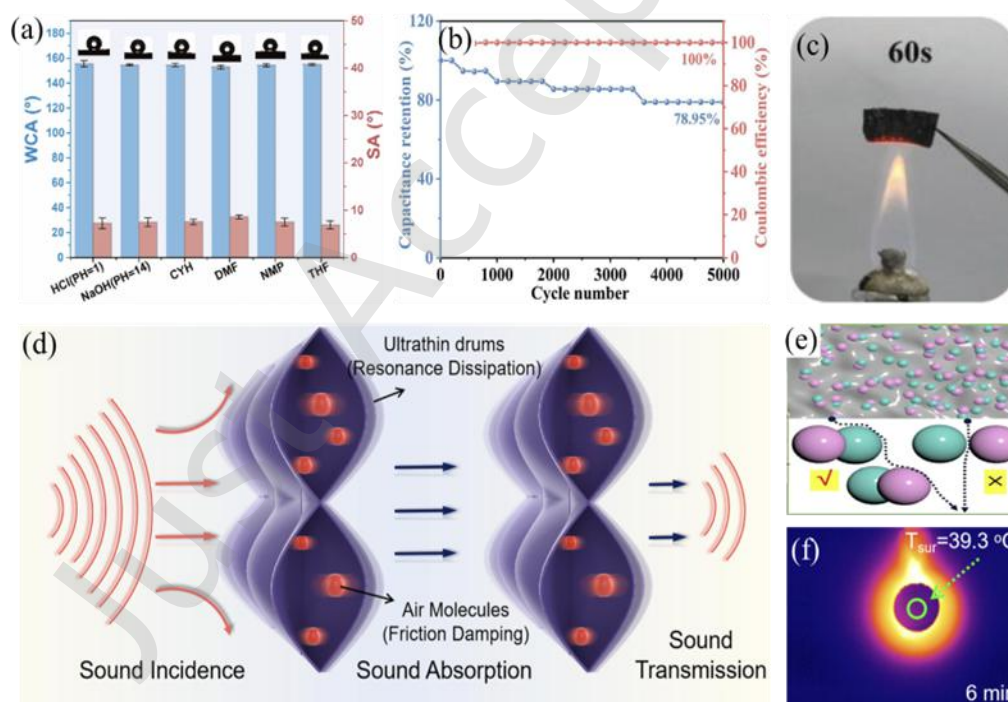


Figure 12 Multifunctional Integrated Design and Intelligent-Response Graphene-Based Composites 1. (a) resistance to organic solvent of rGO/LDH/PPy. Reproduced with permission from Ref. [161] © Elsevier Ltd. 2024. (b) cycling performance and coulombic efficiency for RCS2-12 sample. Reproduced with permission from Ref. [162] © Elsevier Ltd. 2025. (c) Flame retardant tests of GCH-7. Reproduced with permission from Ref. [163] © Elsevier Ltd. 2025. (d) The multiple mechanisms of the polyimide-based acoustic absorber to achieve superior absorption by the resonance of porous polyimide membranes and ultrathin graphene, as well as air friction damping in pores and (f) Thermal infrared images of S3 after 6 min of heating. Reproduced with permission from Ref. [164] © Elsevier Ltd. 2026. (e) Schematic of the corrosion protection mechanism of FZC-1. Reproduced with permission from Ref. [159] © Xu et al 2025.

6.3 Challenges in Extreme Environments: Aerospace and Stealth

In aerospace, battlefield stealth, and other extreme environments, absorber materials must endure high temperatures, strong impacts, and complex electromagnetic

radiation. Traditional absorber materials are prone to thermal degradation and physical failure, highlighting the urgent need for composite materials with both high-temperature stability and mechanical strength [166, 167]. Cai et al. developed a unique sandwich multilayer structure

of ultra-flexible and high-strength graphene paper via directional pressure filtration (Fig. 13a and 13d). Using CNTs@C/CoNi and rGO@C/CoNi as skin and core layers, respectively, they achieved an RL of -66.03 dB and an EAB of 5.0 GHz. The transition layer between the skin and core layers enabled smooth interlayer transitions, resulting in a self-supporting, ultraflexible, electromagnetic wave absorbing composite with high strength and stretchability. The material exhibited a maximum tensile strength of 21.6 MPa and a tensile strain of 11.5%, capable of being folded along sharp creases without damage [168] Du et al. prepared a multiscale carbon fiber/epoxy composite (CFC/GCA/EP) using directional freeze-drying technology. This composite demonstrated wideband absorption performance and excellent delamination and impact resistance (Fig. 13b and 13c), achieving a RL of 8.92 GHz at a thickness of 2 mm. The interlayer distribution of graphene oxide (GO) created an efficient stress transfer network, simultaneously enhancing the material's strength and toughness [169]. Cui et al. developed a scalable, flexible, ultra-thin (0.1 mm), high-surface-density (106 g/m²), and heat-resistant (≥ 1000 °C) graphene@silica fabric supermaterial (G@SFM) via chemical vapor deposition and subtractive laser "erasure" techniques

(Fig. 13e). This material exhibited exceptional durability under high-temperature, high-speed airflow, and mechanical stress, making it an ideal candidate for aerospace applications [170]. In addition, emerging all-carbon architectures have recently been recognized as a promising strategy for addressing the challenges associated with electromagnetic wave absorption under extreme environments. For instance, Zhang et al. successfully synthesized a heterostructured diamond-graphene material under moderate high-pressure and high-temperature conditions, in which multilayer graphene was embedded within a nanodiamond framework and covalently bonded to the surrounding diamond matrix. This unique all-carbon architecture effectively overcomes several intrinsic limitations of conventional composite absorbers, including weak interfacial interactions between fillers and matrices, non-uniform filler dispersion, and limited oxidation resistance. Moreover, by tailoring the relative proportion of sp²- and sp³-hybridized carbon, the dielectric properties could be precisely regulated, enabling an outstanding RL_{min} of -60 dB (3.0 mm) together with an EAB of 4.0 GHz (2.7 mm) [171].

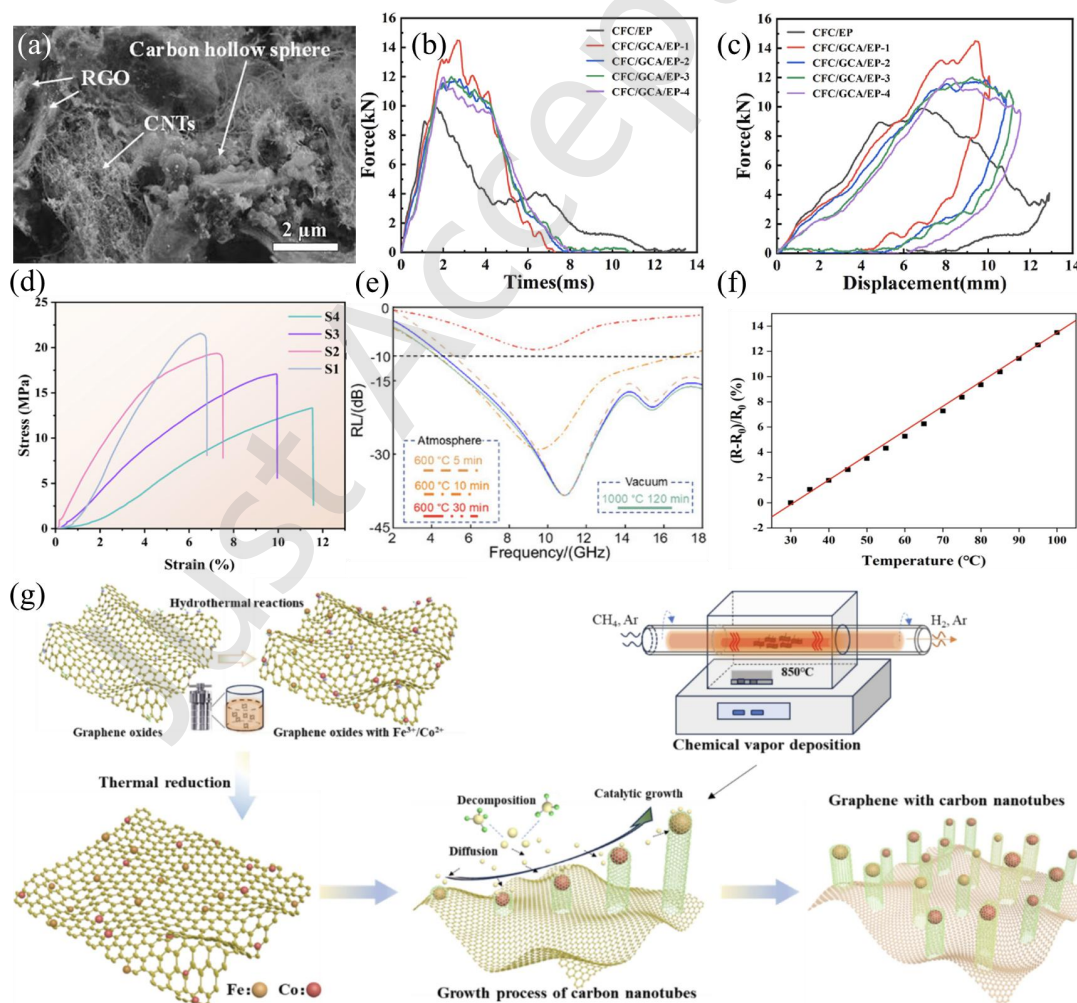


Figure 13 Multifunctional Integrated Design and Intelligent-Response Graphene-Based Composites 2. (a) SEM image of transition layer and (d) Stress-strain curves of sandwich-structured buckypaper. Reproduced with permission from Ref. [168] © Elsevier Ltd. 2026. Drop hammer impact performance of different composites (b) Load-time curves (c) Load-displacement curves. Reproduced with permission from Ref. [169] © Elsevier Ltd. 2026. (e) EMW absorption performance of G@SFM absorbers under different thermal treatment conditions. Reproduced with permission from Ref. [170] © Wiley-VCH GmbH 2026. (f) The curve of $(R-R_0)/R_0$ - temperature and (g) Schematic diagram of rGO-CNTs synthesis process and principle.

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6.4 Intelligent Response and Adaptive Systems

In addition, recent years have witnessed the emergence of absorber materials endowed with unique stimulus-responsive functionalities. Such systems integrate electromagnetic attenuation with intelligent adaptive behavior, offering new paradigms for the development of smart and multifunctional absorbers. Materials exhibiting thermosensitive effects, photothermal conversion, or phase-change-mediated regulation can autonomously adjust their absorption characteristics in response to external stimuli, thereby enabling dynamically tunable electromagnetic protection coupled with adaptive energy management [173]. As shown in Fig. 13f and 13g, Tian et al. employed a combination of hydrothermal synthesis and chemical vapor deposition to anchor carbon nanotubes onto graphene, producing a thermosensitive intelligent absorber (rGO-CNTs). At a thickness of 1.6 mm, the material achieved a $RL_{\min}$ of -37.7 dB, while simultaneously exhibiting high sensitivity and excellent stability in thermal sensing. Within the temperature range of 30-100 °C, the material demonstrated a well-fitted linear relationship between $(R-R_0)/R_0$ and temperature, with a slope of 0.2 %·°C⁻¹ [172]. Li et al. fabricated a 3D Fe₃O₄@GO-CNT adaptive multifunctional phase-change composite absorber by decorating Fe₃O₄ nanoparticles onto a GO-CNT framework through hydrogen-bond-mediated self-assembly. The composite delivered a $RL_{\min}$ of -40.9 dB at a thickness of 2.6 mm and achieved an EAB of 7.7 GHz at 3 mm. Compared with pure PEG, the thermal conductivity of the composite increased by 160%. Moreover, it exhibited exceptional optical absorption, an ultrahigh photothermal storage capacity, and a photothermal conversion efficiency of up to 97%, highlighting its considerable potential for intelligent electromagnetic protection and advanced energy-regulation applications [174].

7 Conclusion and Future Perspectives

Graphene, as a material of significant scientific interest, possesses intrinsic advantages such as high electrical conductivity, large specific surface area, and low density, endowing it with broad application prospects in the field of electromagnetic wave absorption. Nevertheless, its inherently high complex permittivity often leads to impedance mismatch. Although researchers have attempted to optimize its properties through functionalization, heteroatom doping, and the construction of three-dimensional architectures, graphene alone remains insufficient to satisfy the modern requirements of “thin, light, broad and strong”. Consequently, the integration of graphene with other absorptive constituents has emerged as a promising strategy to engineer composites with diverse loss mechanisms, distinctive microstructures, synergistic effects, stable physicochemical properties, and superior absorption performance. This review has summarized recent advances in graphene synthesis methods, and, by classifying absorbers according to their compositional complexity, has presented representative unary, binary, and ternary graphene-based absorbers along with their respective advantages and limitations. Despite encouraging progress, several critical issues remain to be addressed:

(a) Quantifying contributions of distinct absorption mechanisms

Although multiple explanations have been proposed to elucidate absorption mechanisms, a comprehensive and unified model remains elusive. In composite systems, electromagnetic absorption is closely tied to microstructure and composition, yet compositional modifications frequently induce concurrent structural changes, complicating quantitative assessment of individual loss mechanisms. Future efforts should focus on isolating methods that selectively influence specific mechanisms, while integrating theoretical simulations with systematic experimental analysis to achieve quantitative insights. Such studies would provide a scientific basis for precise regulation of composite absorber performance.

(b) Incorporating machine learning and AI-assisted synthesis

Conventional synthesis approaches typically rely on adjusting component ratios or sample thickness to fabricate absorber series for performance evaluation. However, time, cost, and resource limitations often impede exhaustive exploration, and the best-performing experimental sample may not represent the material's theoretical absorption limit. Manual synthesis, testing, and optimization remain laborious and slow. Machine learning and advanced AI models hold promise for predicting optimal impedance-matching thicknesses and rational material combinations, thereby accelerating discovery, improving efficiency, and expediting the development of next-generation absorbers.

(c) Expanding microstructural possibilities and synergistic integration

Graphene-based absorbers have already evolved toward diversified microstructures, which extend propagation paths and enhance loss mechanisms within limited volumes. Moreover, the introduction of heterojunctions enables uniform component distribution, mitigating issues of interfacial delamination and adhesion arising from mismatched physicochemical properties. Designing microstructures with greater functionality and stability thus represents a powerful strategy for improving absorber performance. Furthermore, hybridizing two or more advantageous microstructural designs may achieve complementary effects analogous to graphene's composites with other materials, thereby unlocking new pathways toward multifunctional and high-performance absorbers.

(d) Evolving from intrinsic regulation to intelligent multifunctional systems

The development of graphene-based electromagnetic wave absorbing materials has progressively evolved from intrinsic property regulation toward multicomponent integration and, more recently, intelligent multifunctional systems. Future research should move beyond simply increasing material complexity to establishing multiscale design principles that seamlessly couple composition, structure, and function. Such an evolution is expected to enable adaptive, lightweight, and high-performance absorbers with enhanced environmental compatibility, thereby accelerating their transition from laboratory demonstrations to practical engineering applications.

(e) Developing electrically tunable and intelligently responsive absorbers

Despite the considerable progress achieved in static graphene-based composite absorbers, most reported systems still exhibit fixed electromagnetic responses after fabrication. Taking advantage of graphene's electrically tunable Fermi level, future efforts could be directed toward active metasurfaces and switchable absorbers that allow external-field-driven modulation of impedance matching and absorption behavior. Such intelligent and adaptive systems are expected to broaden the application scope of graphene-based absorbers in complex and rapidly changing electromagnetic environments.

Data availability

Not applicable.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution statement

Z. N. Liu and H. J. Yue conceived the study, conducted the literature review and drafted the manuscript. H. J. Yue and X-B Chen supervised the project and critically revised the manuscript. All authors contributed to the interpretation of the literature, discussed the content, and approved the final version of the manuscript.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

None.

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