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Jiahong Ren, Heguang Liu(✉), Na Tian, Jieli Lyu, Caiyin You(✉)

School of Materials Science and Engineering, Xi'an University of Technology, Xi'an 710048, China

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Review Article

Regulation of interactions between MXenes and magnetic components for microwave absorption: From fundamentals to implementation

Jiahong Ren, Heguang Liu*, Na Tian, Jieli Lyu, Caiyin You*

School of Materials Science and Engineering, Xi'an University of Technology, Xi'an 710048, China

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✉ Address correspondence to Heguang Liu, heguangliu@xaut.edu.cn; Caiyin You, caiyinyou@xaut.edu.cn



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ABSTRACT:

The widespread usage of contemporary communication and electronic devices has rendered electromagnetic radiation and interference prominent environmental concerns. This has prompted the design development of innovative high-efficiency microwave absorption materials (MAMs). MXene-based composites demonstrate potential in this domain owing to their superior intrinsic electromagnetic characteristics. By integrating magnetic nanomaterials, the resultant composites may establish a distinctive “magnetic-dielectric” dual-loss network via regulation of interaction between magnetic nanomaterials and MXenes. This network efficiently integrates the superior charge-transfer properties of MXenes with the magnetic loss processes of magnetic nanomaterials, which is fundamental to boosting microwave absorption performance. In the past few years, significant accomplishments have been achieved in this aspect. Herein, we intend to systematically summarize the theoretical foundations and recent advancements in magnetic nanomaterial-reinforced MXene MAMs. First, we evaluate the loss mechanisms at heterogeneous interfaces of magnetic MXene MAMs. Secondly, we classify and assess the construction methodologies and the interaction regulation strategies for various magnetic systems (comprising magnetic metals, magnetic alloys, magnetic oxides, and magnetic sulfides) on MXene substrates and their corresponding effects on enhancing microwave absorption. Finally, we present the principal challenges faced by contemporary preparation procedures and performance optimization and offer insights into future trends regarding multi-functional integration. This review attempts to provide systematic insights for the design of high-performance MXene-based MAMs and to suggest novel approaches for the technical advancement of electromagnetic protection materials.

KEYWORDS: MXenes; magnetic nanomaterials; microwave absorption; synergistic mechanism; microstructure design

1 Introduction

Electromagnetic waves, as critical carriers of energy and information, have extensively infiltrated the fundamental framework of contemporary industrial and commercial infrastructure following significant advancements in satellite communication, high-density electrical apparatus, and artificial intelligence [1-3]. However, the rapid development of electromagnetic technology has also exposed new challenges. Firstly, stray electromagnetic fields during signal transmission can interfere with the normal operation of precision instruments, leading to degradation of channel capacity and communication link instability, thereby severely undermining the robustness of 5G millimeter-wave communications and low Earth orbit satellite links [4-6]. Secondly, prolonged exposure to electromagnetic environments exceeding safety thresholds may impair sleep quality and induce cumulative bioelectromagnetic effects, posing potential risks to human health [7-10]. More critically, electromagnetic signature emissions from weapon platforms significantly increase their radar cross section (RCS), diminishing the survivability of stealth aircraft and precision-guided weapons systems and presenting severe threats to national defense security [11-13]. As a result, MAMs, which can convert incident electromagnetic energy into heat energy, have emerged as a prominent research focus across multiple disciplines [14, 15].

Conventional MAMs, based on electromagnetic wave loss mechanisms, are generally divided into dielectric-loss-dominated type and magnetic-loss-dominated types, including ferrites, magnetic metals, conductive polymers, and ceramic-based composites [16, 17]. Despite the widespread utilization of these materials, their inherent limitations, including high density, narrow absorption bandwidth, and insufficient environmental durability, render them progressively incapable of satisfying the demands in emerging application scenarios [18-20]. Consequently, there is an urgent need for MAMs to evolve towards “lightweight, thin, broadband, and strong absorption” characteristics [21-23]. Compared to traditional bulk absorbing materials, MXenes have emerged as one of the most promising alternative candidates

MAMs. MXenes are a widely studied class of two-dimensional (2D) layered materials, typically consisting of transition metal carbides, nitrides and carbonitrides, with a general chemical formula of $M_{n+1}X_nT_x$ ($n = 1, 2, 3$). In this formula, M represents transition metals, such as Ti and V, X corresponds to carbon or nitrogen, and T_x denotes the various terminal functional groups terminated on the MXene surface, including -OH, -O, and -F [24-26]. MXenes possess a high specific surface area, distinct quantum confinement effect, unique electron transport properties, and rich surface chemistry, making them a key system for developing new high-performance MAMs [27-29]. However, MXenes face specific challenges in MAM applications: first, layer stacking reduces multiple reflections and interfacial polarization losses [30, 31]; second, overreliance on dielectric loss mechanism often results in a narrow effective absorption bandwidth (EAB) [32, 33]; third, high electrical conductivity always induces the skin effect, causing impedance mismatch and leading to significant reflection of incident waves at the material interface [24, 34].

The integration of magnetic nanomaterials into MXenes addresses these issues by synergistically combining magnetic loss with dielectric loss mechanisms. For instance, Xiang's team deposited sea urchin-like carbon nanotubes (CNTs)/Co composites onto $Ti_3C_2T_x$ MXene sheets, achieving a minimum reflection loss (RL_{min}) of -85.8 dB, with an EAB of 6.1 GHz at an ultra-thin thickness of only 1.4 mm, and the filler loading was as low as 5 wt.% [35]. Cheng et al. assembled Ni/MXene hybrids architectures supported by melamine foam, which delivered a RL_{min} of -62.7 dB at a thickness of 2 mm, and reached an EAB of 6.88 GHz at a thickness of 1.8 mm [36]. These studies collectively demonstrate that incorporating magnetic nanomaterials not only utilizes magnetic loss mechanisms including natural resonance, exchange resonance, and eddy current loss, but also suppresses MXene layer stacking through the steric hindrance effect. This effective tuning of the composite's electromagnetic parameters and optimizing of impedance matching, enabling efficient broadband absorption at thin thicknesses [37-42].

Although significant progress has been made in developing magnetic nanomaterial-reinforced MXene composites for microwave absorption, existing

reviews predominantly focus on specific composite systems such as MXenes combined with metal-organic framework derivatives or spinel ferrites [43, 44]. There remains a lack of comprehensive comparison and in-depth analysis of the underlying mechanisms by which different classes of magnetic nanomaterials (e.g., pure metals, metal alloys, metal oxides, metal sulfides) enhance the microwave absorption performance of MXene-based composites. Therefore, this review comprehensively evaluates the latest research progress in magnetic nanomaterial-reinforced MXene MAMs (Fig. 1). We specifically outline four representative magnetic nanomaterials commonly employed to enhance MXene-based composites, including magnetic metals, magnetic alloys, magnetic oxides, and magnetic sulfides. In the present review, first, we illustrate the electromagnetic wave attenuation mechanisms of both MXene and magnetic nanomaterials. Second, we perform a comparative statistical analysis of the microwave absorption performance of distinct magnetic nanomaterial/MXene composite systems. Focusing on core performance indicators including $RL_{\min}$, EAB, and matching thickness, we clarify the synergistic interaction between magnetic components and the MXene matrix, and further summarize the unique contributions of different classes of magnetic nanomaterials to the total magnetic loss capacity of the composites system. Finally, we conclude the key challenges in this field and provide an outlook on future development directions, with the aim of offering guidance for the construction of advance next-generation efficient, lightweight, broadband MAMs.

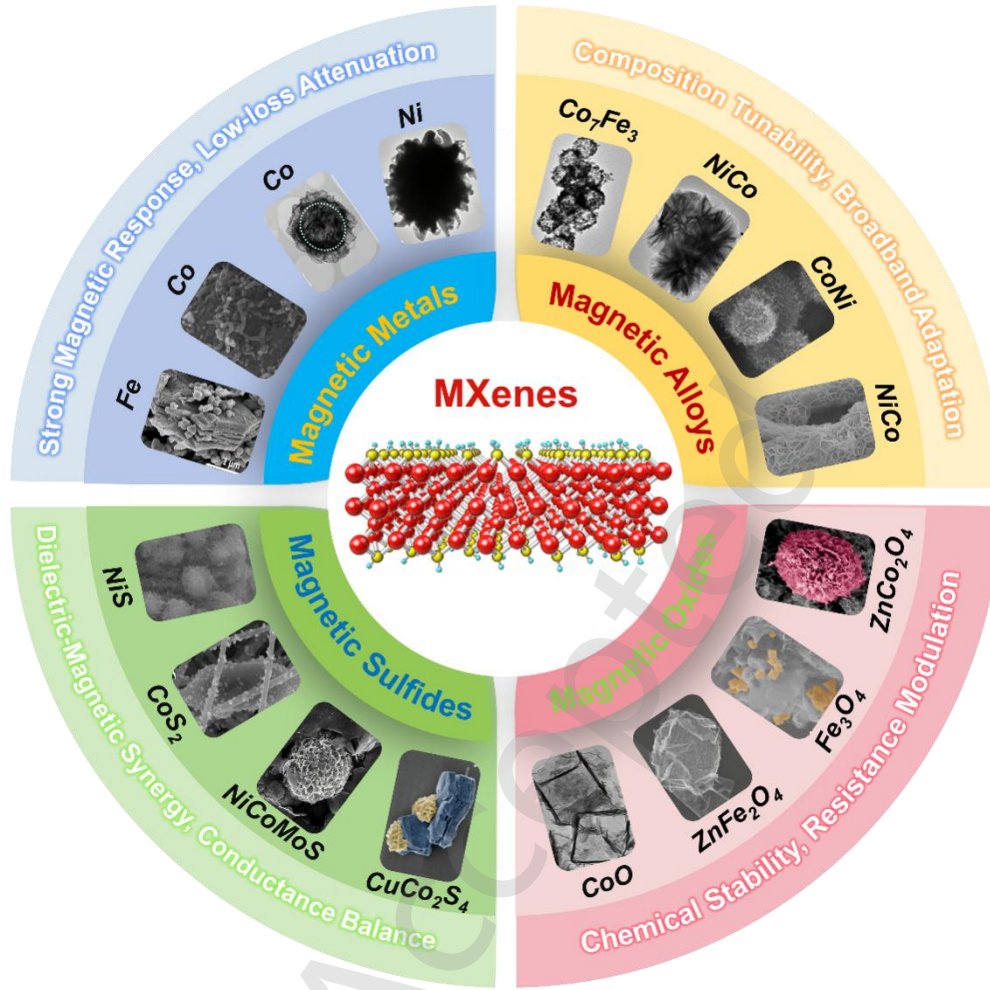


Figure 1 Overview of magnetic nanomaterial-reinforced MXene composites for microwave absorption. Reproduced with permission from Ref. [94], © American Chemical Society 2025. Ref. [103], © Elsevier Ltd. 2022. Ref. [108], © Elsevier Ltd. 2024. Ref. [114], © American Chemical Society 2021. Ref. [122], © Elsevier Ltd. 2024. Ref. [127], © Elsevier B.V. 2021. Ref. [129], © Elsevier B.V. 2023. Ref. [132], © Elsevier Ltd. 2022. Ref. [147], © The Royal Society of Chemistry 2023. Ref. [154], © Elsevier Ltd. 2024. Ref. [159], © Elsevier B.V. 2024. Ref. [165], © Elsevier Ltd. 2025. Ref. [169], © Elsevier Ltd. 2021. Ref.[173], © Elsevier B.V. 2025. Ref. [175], © Elsevier Ltd. 2025. Ref.[176], © Elsevier Inc. 2024.

2 Fundamental microwave absorption theory

The design of high-performance MAMs must simultaneously satisfy two core requirements: excellent impedance matching and strong attenuation capability [45-47]. Impedance matching is a fundamental prerequisite for realizing the optimal performance of MAMs. It requires the normalized input impedance ($Z = |Z_{in}/Z_0|$) to approach unity ($Z \approx 1$). This condition minimizes the reflection of incident electromagnetic waves at the air-material interface, allowing maximum energy to

penetrate into the interior of the material [48, 49]. Once electromagnetic waves enter the material, efficient attenuation capability becomes the key to achieving effective absorption, which relies on dielectric loss and magnetic loss mechanisms to convert incident electromagnetic energy into heat energy [50]. Materials' electromagnetic properties are defined by complex permittivity ($\epsilon_r = \epsilon' - j\epsilon''$) and complex permeability ($\mu_r = \mu' - j\mu''$). The real parts ϵ' and μ' , which correspond to electric energy storage and magnetic energy storage capability respectively, mainly govern the efficiency of impedance matching by regulating the refraction behavior of electromagnetic waves at the air-material interface. The imaginary parts ϵ'' and μ'' reflects how effectively the material can dissipate electromagnetic energy in the form of heat. The efficiency of these loss mechanisms is evaluated by the dielectric loss tangent ($\tan\delta_E = \epsilon''/\epsilon'$) and the magnetic loss tangent ($\tan\delta_M = \mu''/\mu'$). Under favorable impedance matching conditions, higher $\tan\delta_E$ and $\tan\delta_M$ values contribute to achieving significant RL and a broader EAB [17, 51, 52]. A schematic diagram illustrating the multiple microwave absorption mechanisms of the material is presented in Fig. 2. In addition to intrinsic loss mechanism based on permittivity and permeability, multiple scattering within the material structure provides an important pathway to enhancing electromagnetic wave attenuation. Multiple scattering can be introduced by rational design of porous architectures or heterogeneous interfaces, which extend the effective propagation path of incident waves. This mechanism works synergistically with dielectric and magnetic losses, ultimately improving the overall energy dissipation efficiency of the MAMs [53].

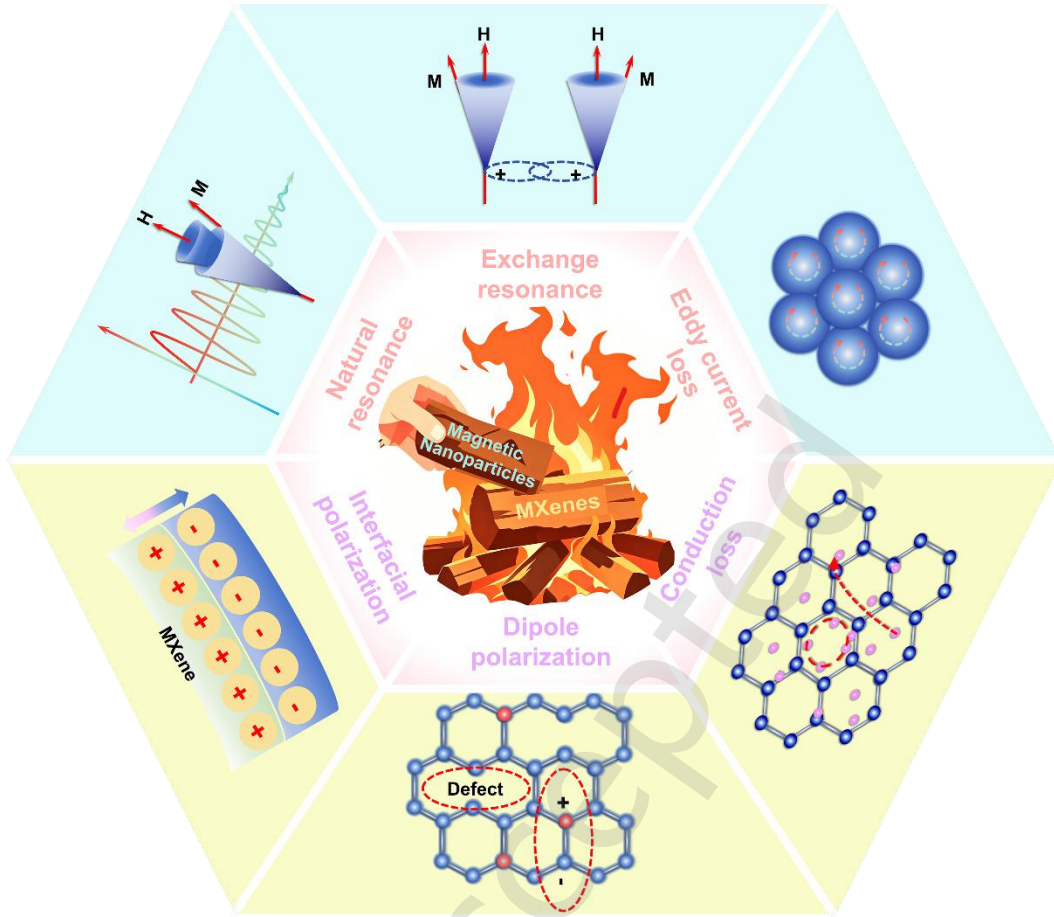


Figure 2 Scheme of the dielectric-magnetic synergy loss mechanism

2.1 Dielectric loss

The contribution of dielectric loss to electromagnetic wave attenuation is primarily derived from conduction loss (ϵ_c'') and polarization relaxation loss (ϵ_p'') [54]. Conduction loss arises from the directional drift of free charges under an alternating electric field, and the kinetic energy of these migrating charges is dissipated as Joule heat through collisions with lattice defects and phonons [55]. Based on the free-electron theory, conduction loss contribution to permittivity imaginary part can be expressed as [56, 57]:

$$\epsilon_c'' = \frac{\sigma}{\omega \epsilon_0} \quad (1)$$

where σ is the electrical conductivity (S/m); ω denotes the angular frequency, defined as $\omega = 2\pi f$; and ϵ_0 denotes the vacuum permittivity. This mechanism dominates dielectric loss in the low-frequencies regime ($f < 10^6$ Hz), but diminishes significantly at higher frequencies due to decreasing efficiency of charge migration.

MXenes exhibit exceptionally high intrinsic electrical conductivity, which can be attributed to two synergistic factors [2]: Electronic band structure effect and 2D confinement effect. The hybridization between the d-orbitals of transition-metal and the p-orbitals of C/N can increase the density of states in the vicinity the Fermi level, providing abundance free charge carriers and endowing MXenes with metal-like conductivity. Weak interlayer coupling and shortened electron mean free paths suppress phonon scattering, which ultimately leads to high carrier mobility in MXenes [58-60]. Size-dependent conductivity effects become significant at nanoscale dimensions when the particle size approaches or falls below the electron mean free path. Quantum confinement and enhanced surface scattering can induce non-monotonic variations in electrical conductivity. Monolayer MXenes generally exhibit superior conductive loss efficiency due to minimized interlayer scattering. However, while high conductivity enhances ϵ_c , excessive values promote continuous conduction currents, intensifying the skin effect. This exacerbates impedance mismatch at the air-material interface [61]. Consequently, achieving optimal conductivity is crucial for balancing attenuation capability and impedance matching.

Polarization relaxation loss stems from two primary sources: the delayed reorientation of electric dipoles (e.g., from surface functional groups and vacancy-defect complexes), and the lagged response of accumulated charges at heterogeneous interfaces under an alternating electric field. This asynchrony between dipole/charge and the oscillation of the external field results in the dissipates of electromagnetic energy in the form of heat. While electronic polarization occurs at PHz frequencies and is negligible in the microwave band, ionic polarization can still contribute to microwave loss of MXenes in the GHz range [27, 54, 62].

Defect-induced dipolar polarization: Surface terminations (-F, -O, -OH) and vacancies introduced during etching create localized dipole moments, which act as Debye-type relaxation centers. Due to asymmetric charge distributions, charge carriers trapped at these defect sites can form transient dipoles under an applied field. The reorientation of these dipoles exhibits a characteristic relaxation lag, dissipating energy when thermal randomization lags the field reversal.

Interfacial polarization (Maxwell-Wagner-Sillars effect): Layered MXene structures, termination gradients, and heterogeneous interfaces within composites create regions with sharp dielectric contrast and conductivity gradients. At these phase boundaries, space charges accumulate forming macroscopic dipoles. Potential barriers hinder charge migration across interfaces, causing a delayed response during field oscillation. This asynchrony converts electromagnetic energy into heat through resistive loss [2, 63].

The frequency dependence of complex permittivity resulting from polarization relaxation can be well described by the Debye polarization relaxation model. For a single relaxation process, it is given as follows [64, 65]:

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau} \quad (2)$$

where ε^* is the complex permittivity; ε_s is the static permittivity; ε_∞ is the permittivity at the high-frequency limit; ω is the angular frequency, and τ is the characteristic polarization relaxation time. The real (ε') and imaginary (ε'') parts of permittivity can be further derived as [66, 67]:

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\omega\tau)^2} \quad (3)$$

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + (\omega\tau)^2} \quad (4)$$

These two components satisfy the intrinsic Kramers-Kronig relationship, which is expressed as [68, 69]:

$$\left(\varepsilon' - \frac{\varepsilon_s + \varepsilon_\infty}{2}\right)^2 + (\varepsilon'')^2 = \left(\frac{\varepsilon_s - \varepsilon_\infty}{2}\right)^2 \quad (5)$$

Cole–Cole plots, which describe the relationship between ε'' and ε' , are powerful tools for deconvoluting different dielectric loss mechanisms. An ideal single Debye relaxation process presents as a perfect semicircle in the plot [70]. In MXenes and their composites, multiple overlapping semicircles or depressed semicircular arcs are frequently observed, indicating a distribution of relaxation times. This typically arises from the combined contributions of dipolar polarization and interfacial polarization at heterogeneous boundaries. A low-frequency tail with a slope close to 1 implies remarkable conductive loss, which is prominent in highly conductive MXene

networks. The deviation from ideal semicircular geometry, which is usually represented by the Cole-Cole distribution parameter α , can reflect the heterogeneity of polarization centers in the material. Moreover, a steeper rise in the low-frequency tail of the ε'' curve is associated with stronger resistive loss and more efficient electromagnetic energy attenuation [71-74].

2.2 Magnetic loss

Magnetic loss in GHz frequency range for magnetic nanomaterials can mainly be attributed to three fundamental mechanisms: natural resonance, exchange resonance, and eddy current loss [75, 76].

Natural resonance, also widely known as zero-field ferromagnetic resonance, occurs when the frequency of the incident alternating magnetic field matches the inherent precession frequency of the magnetic moments that exist within the bulk of the material. Under such a resonance condition, the amplitude of magnetic moments precession undergoes coherently amplification, enabling efficient energy conversion from electromagnetic waves to lattice vibrations. Natural resonance typically dominates the magnetic loss spectrum in the 2–10 GHz frequency range. For a spherical demagnetized sample, the resonance frequency f_r can be expressed by the classical Kittel equation [77-79]:

$$f_r = \frac{\gamma}{2\pi} H_a \quad (6)$$

where γ denotes the gyromagnetic ratio, and H_a represents the effective anisotropy field. This field combines contributions from three main sources: magnetocrystalline anisotropy field (H_k), magnetostatic shape anisotropy, and externally applied static magnetic field (H_{dc}), strategically enhancing H_k or engineering high-aspect-ratio morphologies can increase f_r . This allows natural resonance to operate at higher frequency ranges while maintaining efficient energy dissipation [78]. Based on the quarter-wavelength matching principle, the absorber reaches optimal impedance matching when its thickness t_m satisfies the following condition [80, 81]:

$$t_m = \frac{n\lambda}{4} = \frac{nc}{4f_m\sqrt{|\mu_r||\varepsilon_r|}} \quad (n=1, 3, 5, \dots) \quad (7)$$

in which c stands for the speed of light in free space, f_m is the target absorption

frequency, μ_r , ε_r refer to the relative complex permeability and permittivity, respectively. When the natural resonance frequency f_r of the material increases, the required matched thickness t_m can be correspondingly reduced to maintain quarter-wavelength impedance matching, which provides a feasible strategy for designing thin and lightweight MAMs [82].

Exchange resonance corresponds to quantized spin-wave modes that dominant in magnetic nanoparticles (diameter $D < 50$ nm) with high surface-to-volume ratios. Its characteristic resonance frequency f_{exc} typically exceeds 10 GHz due to enhanced surface anisotropy contributions, making it a key mechanism for breaking the Snoek limit and realizing high-frequency MAMs. For single-domain spherical ferromagnetic nanoparticles, f_{exc} is described by the Aharoni equation [57, 75, 78]:

$$f_{exc} = \frac{\gamma}{2\pi} \sqrt{(H_k + H_{surf})(H_k + \alpha H_{surf})} \quad (8)$$

where $H_{surf} = 6K_s/(\mu_0 M_s D)$, K_s represents the surface anisotropy constant (J/m²), α is the dimensionless exchange constant scaling factor, A is the exchange stiffness (J/m), μ_0 denotes the vacuum permeability, M_s corresponds to the material's saturation magnetization. Exchange resonance frequency strongly depends on the effective anisotropy field H_{eff} , which incorporates contributions from magnetocrystalline anisotropy H_k , size effects, geometric anisotropy and interparticle interactions [83].

Eddy current loss originates from Faraday's law of electromagnetic induction. The incident alternating magnetic fields will induce circulating eddy currents inside the conductive magnetic nanomaterials, and the induced currents further dissipating electromagnetic energy as Joule heat via resistive dissipation. At GHz frequencies, the skin effects these currents to generate opposing magnetic fields, confining current flow to the surface layers, which can be characterized by the penetration depth δ [84]:

$$\delta = \sqrt{\frac{2}{\omega \mu_0 \mu' \sigma}} \quad (9)$$

where σ is the DC conductivity (S/m), μ' denotes the real part of complex permeability, and $\omega = 2\pi f$ represents the angular frequency (rad/s). The eddy current coefficient (C_0) serves as a critical metric to evaluate the dominance of this loss mechanism [85, 86]:

$$C_0 = \mu'' \cdot (\mu')^{-2} f^{-1} \quad (10)$$

This coefficient provides a quantitative criterion for identification the dominant mechanism in the GHz frequency range: if C_0 remains approximately constant across the measured frequency band, eddy current loss predominantly the governs magnetic dissipation; if C_0 shows obvious frequency-dependent variation, the magnetic loss is dominated by resonance processes (natural/exchange resonant) [87, 88].

3 Design of MXene-based MAMs with magnetic components

3.1 Magnetic metal-enhanced MXene MAMs

Ferromagnetic metals (Fe, Co, Ni) are typical ferromagnetic 3d transition metals, are ideal candidates for constructing millimeter-wave absorbing materials, owing to their high M_s and intrinsic multi-band magnetic loss mechanisms [89-91].

3.1.1 Iron

Iron (Fe), a representative cost-effective soft magnetic material, exhibits exceptional room-temperature M_s and a high Curie temperature (T_c). These intrinsic properties endow it with excellent thermal stability, and enable a strong frequency-dependent complex permeability responses to alternating electromagnetic fields over a wide operating temperature range [92, 93].

Li's team synthesized high-purity single-phase α -Fe nanoparticles via iron pentacarbonyl pyrolysis, followed by in-situ self-assembly onto Nb_2CT_x nanosheet surfaces to construct $\alpha\text{-Fe@Nb}_2\text{CT}_x$ heterostructures [94]. The study revealed that the BCC structure of α -Fe endows it with high spin polarization and strong magnetic domain wall mobility, which facilitates excellent natural resonance magnetic loss in the microwave band. At 6 wt.% Nb_2CT_x , the composite achieved an EAB of 7.2 GHz at a thin matching thickness of 1.5 mm. When the Nb_2CT_x content increased to 20 wt.%, a $RL_{\min}$ of -49.7 dB was achieved at a matching thickness of 3.3 mm.

However, conventional composite methods often lead to non-uniform MXene functional group distribution and Fe nanoparticle agglomeration, causing unexpected variations in electromagnetic parameters and consequent absorption peak shifts. To address this, Lu's team proposed an inverse design strategy based on the

size-harmonization law for the Fe/MXene system [95]. By embedding small-sized Fe nanoparticles within MXene interlayers, they achieved simultaneous regulation of dielectric relaxation behavior and natural resonance frequency, effectively suppressing electromagnetic parameter fluctuations that induce absorption band drift. Specifically, the MTF-2 sample exhibited a minimal frequency deviation of only 0.24 GHz (error $\sim$ 69%), while its EAB was enhanced by 325%. This result clearly demonstrates the efficacy of heterointerface engineering and targeted electromagnetic parameter tuning for precise low-frequency microwave absorption. Mechanistically, optimal Fe doping suppresses excessive MXene interlayer expansion, maintaining appropriate electrical conductivity for conduction loss while introducing defects and functional groups that enhance interfacial polarization relaxation and space charge density. As Fe content increases, the former heterointerfaces generate strong built-in electric fields, shifting polarization mechanisms from dipole relaxation dominance to space-charge polarization governed by dual interfaces (MXene-TiO₂ and MXene-Fe). This interfacial engineering strategy, coupled with directional electromagnetic parameter coordination, is pivotal for achieving accurate low-frequency microwave absorption [96].

3.1.2 Cobalt

Cobalt (Co), another representative 3d ferromagnetic metal, exhibits a slightly lower M_s than Fe but possesses a higher T_c . This ensures robust magnetic thermal stability over a broad temperature range, far exceeding the thermal stability limits of conventional soft magnetic ferrites [97, 98].

As illustrated in Fig. 3a, Peng's group constructed multi-heterointerface Co@NC composites on MXene substrates using an electrostatic self-assembly strategy [101]. By optimizing the Co@NC loading content, the sample achieved an EAB of 6.93 GHz with a matching thickness of 1.8 mm when the loading was set to 25 mg. Micromagnetic simulations were employed to visualize the magnetic domains evolution within nanoparticles and the interparticle magnetic interactions (Fig. 3c). The low-frequency absorption mainly originates from hysteresis loss due to delayed

magnetic moment reversal. At high frequencies, energy dissipation is dominated by domain wall migration that pinned by crystal defects, while full-spectrum magnetic loss is closely related to the perturbation induced by dynamic magnetic moment fluctuations. Importantly, the magnetic coupling network between Co nanoparticles overcomes the size limitation of individual nanoparticles, enabling broadband strong absorption. Without the induction of an external magnetic field, cobalt particles exhibit isolated domain structures and the magnetic moments of different particles are independently oriented, leading to dispersed energy dissipation paths. Upon field application, the synchronized moments form a collective single-domain response, which generates dynamic hysteresis loss by overcoming the torque imbalances caused by initial orientation disparities and particle inhomogeneity. Thus, strategically designed dislocation defects can enhance high-frequency performance via domain wall pinning [99]. To address the issue that conventional absorber over-rely on single electromagnetic coupling mechanisms, Peng's team further designed a multilayer gradient metamaterial based on MXene/Co@NC-2. Finite element simulations guided by quarter-wavelength theory determined optimized layer thicknesses. As shown in Fig. 3b, the strongest absorption is concentrated at the edges where resonance effects dominate. The interlayer resonance coupling induced by $\lambda/4$ phase difference enriches the loss mechanisms, which directly overcomes the limitation of single mechanisms, and finally achieves an ultrabroadband absorption bandwidth of 12.72 GHz [100].

Although MXene matrices improve the dispersion of Co nanoparticles, they often concurrently weaken the overall magnetic coupling strength. To resolve this trade-off, Pan's team innovatively proposed a magnetic-field-induced self-assembly technique (Fig. 3d) [102]. In this process, 0D Co nanoparticles align into 1D chains under an external parallel magnetic field. This unique configuration introduces strong shape anisotropy and domain wall pinning effects, significantly enhancing H_c and magnetic coupling intensity. The as-fabricated MXene-CoC multilayer heterostructure achieves synergistic optimization of electromagnetic parameters, exhibiting higher permittivity than the MXene-CoP. The enhanced performance primarily stems from the distinct domain motion behavior and magnetic flux line characteristics inherent to

the 1D magnetic chains. A comparative illustration of the absorption mechanisms for MXene-CoC and MXene-CoP is presented in Fig. 3e. The chain-induced magnetic anisotropy drives more efficient magnetic domain motion, substantially increasing magnetic energy storage capacity. Unlike isolated dispersed particles, the inter-particle magnetic coupling within the 1D chain promotes a semicircular distribution of magnetic flux lines. Furthermore, inter-chain coupling forms a closed-loop magnetic network, which collectively intensifies magnetic loss efficiency. The proposed IMFFE effect establishes this re-circulating, high-density magnetic flux network through a combination of dynamic domain response, enhanced magnetic anisotropy, flux redistribution and inter-chain coupling, enabling the MXene-CoC composite to achieve a $RL_{\min}$ of -46.48 dB, with the corresponding matching thickness being just 1.02 mm.

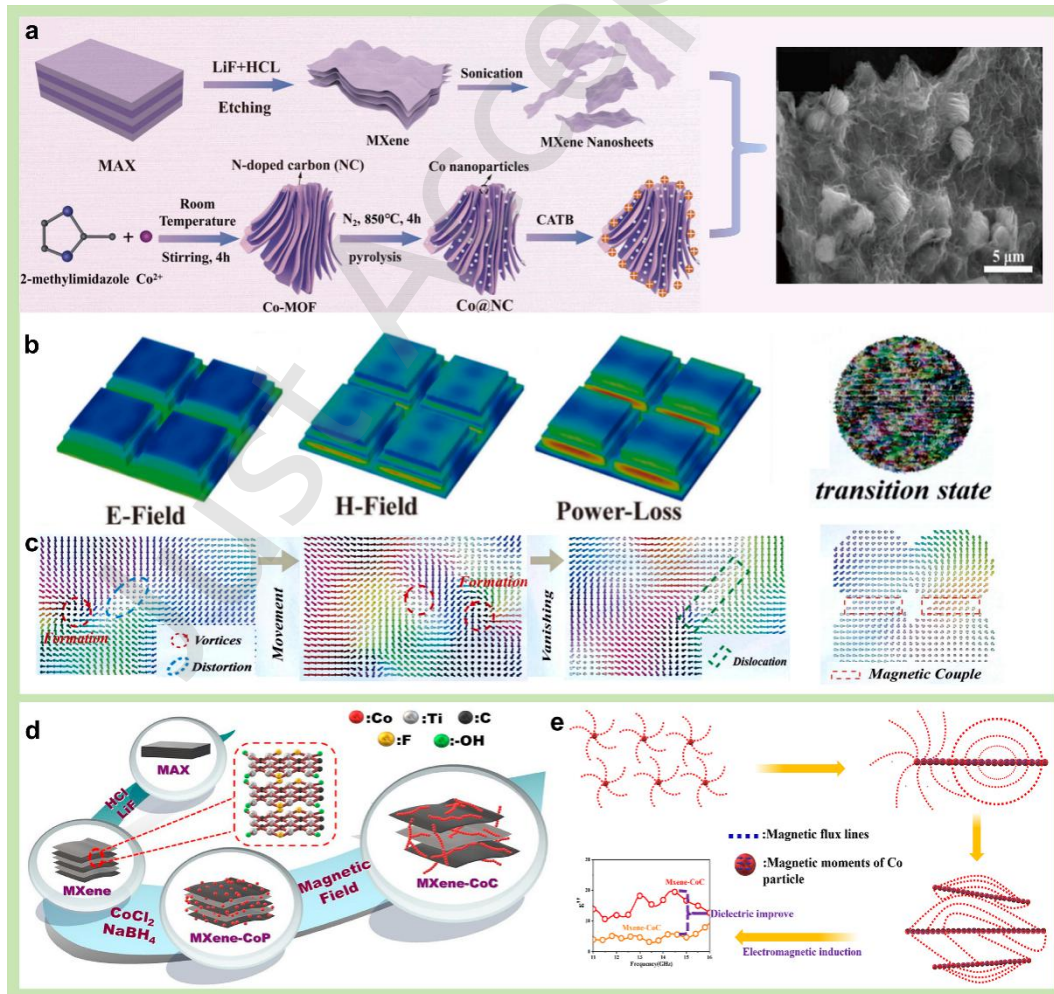


Figure 3 (a) Preparation flowchart of MXene/Co@NC composites. (b) Schematic diagram of the electric field, magnetic field, and power-loss distributions of MCNC-2. (c) Magnetic domain

evolution process and magnetic coupling results of single/multiple cobalt nanoparticles under an alternating magnetic field. Reproduced with permission from Ref. [101], © Elsevier B.V. 2025. (d) Preparation flowchart of MXene-CoC composites. (e) Schematic diagram of IMFFE principle. Reproduced with permission from Ref. [102], © Elsevier Ltd. 2020.

Multiple research groups have significantly enhanced microwave absorption performance by constructing multidimensional 0D/1D/2D heterostructures. Zou's group (Fig. 4a) developed in-situ growth of ZIF-67 on monolayer MXene to synthesize Co@C/MXene multi-heterojunctions [103]. By modulating MXene content, they effectively controlled the Co grain size. The optimal sample reached a $RL_{\min}$ of -50.5 dB at the frequency of 5.9 GHz with a thickness of 4.0 mm, while when the thickness was adjusted to 2.0 mm, it delivered an EAB of 5.8 GHz. Zhao et al. (Fig. 4b) anchored 0D Co nanoparticles onto the tips of 1D CNTs and compounded them with 2D multilayered MXene. Precise regulation of the CNT content facilitated the high dispersion of Co nanoparticles, not only effectively inhibits the agglomeration and oxidation degradation of the magnetic nanoparticles, but also constructs a 3D interconnected conductive network, which ultimately improves the conduction loss. This composite achieved a $RL_{\min}$ of -62.53 dB at a thin matching thickness of 1.59 mm, and an EAB of 4.20 GHz at 1.38 mm, covering the frequency range of 12.48–16.68 GHz [104]. Nevertheless, the attenuation performance of such layered composites is often limited by the pronounced self-stacking tendency of MXene nanosheets. Core-shell structures address this limitation through their abundant heterointerfaces, structural anisotropy, and unique cavity configurations, which delivering superior electromagnetic wave attenuation [105, 106]. Zhang and co-workers (Fig. 4c) fabricated hollow MXene@Co microspheres via hydrothermal synthesis using PMMA as sacrificial templates. This configuration achieved a $RL_{\min}$ of -57.32 dB with an $EAB_{\max}$ of 5.2 GHz [107]. Yu's team (Fig. 4d) developed hierarchical MXene@Co/C hollow carbon spheres through electrostatic self-assembly and in-situ reduction processes. By optimizing MXene content, the best-performing sample attained a $RL_{\min}$ of -53.99 dB at matching thickness of 2.1 mm. Additionally, it exhibited an EAB of 7.2 GHz when the thickness was adjusted to 2.0 mm [108].

Therefore, Wu's group constructed a core-shell magnetic absorber named hollow MXene/Multi-walled Carbon Nanotubes (MWCNTs)@C-Co microspheres (HMCCo) using polystyrene (PS) microspheres as sacrificial templates [109]. The fabrication process (Fig. 4e) began with the synthesis of multilayered MXene nanosheets via HCl-LiF etching followed by ultrasonication. Positively charged PS microspheres were prepared through PDDA modification, enabling electrostatic self-assembly of negatively charged MXene nanosheets to form PS@MXene core-shell structures. Subsequently, abundant functional groups on MXene surfaces captured Co^{2+} ions, which acted as binding sites for coordination with organic ligands to grow ZIF-67 crystals in situ on the PS@MXene spheres. Final calcination achieves the simultaneous removal of the template, pyrolysis of ZIF-67, and carbonization of MXene. The resultant microstructure and corresponding absorption mechanism are clearly illustrated in Fig. 4f. During calcination, decomposition products of PS microsphere drive the in-situ growth of numerous MWCNTs toward the interior of spherical shells. Co nanoparticles are embedded at the MWCNT tips, collectively creating a distinctive "exoskeleton-endotube" morphology. Owing to this synergistic structural design, the optimized HMCCo sample achieved a $RL_{\min}$ of -70.70 dB at 14.56 GHz (2.04 mm), with an EAB of 5.67 GHz, covering 12.33–18.00 GHz.

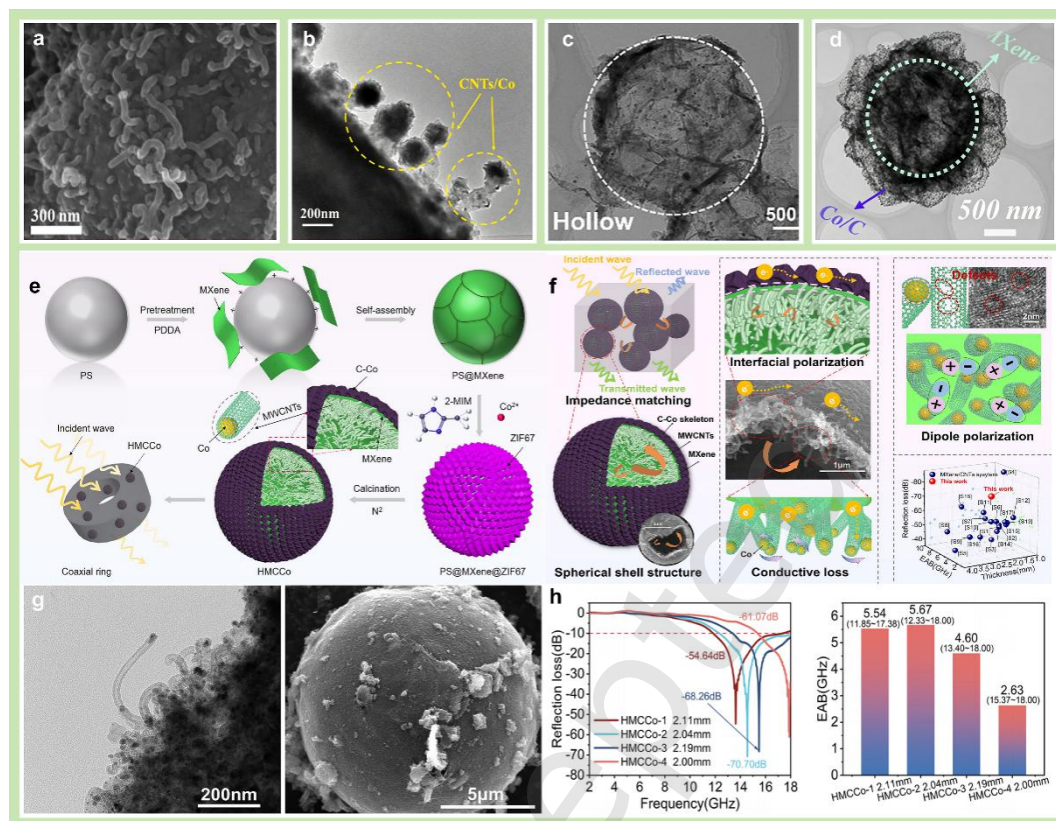


Figure 4 (a) SEM images of Co@C/M-10. Reproduced with permission from Ref. [103], © Elsevier Ltd 2022. (b) TEM images of CNTs/Co. Reproduced with permission from Ref. [104], © Elsevier Ltd. 2024. (c) TEM images of MXene@Co NPs. Reproduced with permission from Ref. [107], © Elsevier Ltd. 2024. (d) HRTEM images of MCC. Reproduced with permission from Ref. [108], © Elsevier Ltd. 2024. (e) Schematic diagram of the synthesis of HMCCo samples. (f) Electromagnetic wave loss mechanism of HMCCo samples. (g) SEM images of the spherical shell surface of the HMCCo-2 sample and TEM images of the internal structure of the fragment edges. (h) Optimal reflection loss and effective absorption bandwidth of samples with different C-Co contents. Reproduced with permission from Ref. [109], © Springer 2024.

3.1.3 Nickel

Nickel nanoparticles exhibit excellent oxidation resistance, moderate electrical conductivity, and tunable magnetic anisotropy. These intrinsic properties make them ideal modifiers for MXene-based composites, enabling significant improvement in electromagnetic wave absorption performance [110, 111].

Wu and co-workers innovatively developed a one-step Lewis acid molten salt method (Fig. 5a) [112]. This approach leverages the strong bonding affinity between aluminum atoms and chlorine ions. During the etching reaction with Ti_3AlCl_2 precursor, the method simultaneously realizes the in-situ reduction and stable

anchoring of Ni^{2+} ions. This strategy successfully fabricated a periodic MXene-Ni-MXene electromagnetic synergistic network, effectively overcoming the limitations of conventional electrostatic assembly, such as weak interfacial interactions, complex processing steps, and uneven distribution of magnetic components. Strong electronic coupling between the in-situ deposited Ni species and the electron clouds on the $\text{Ti}_3\text{C}_2\text{T}_x$ surface promoted the generation of unpaired electron spins within Ti orbitals. Combined with core-level vacancies generated during XPS excitation, this induces prominent multiple splitting of the spectral peaks (Fig. 5b). Such interfacial interactions effectively trigger interfacial and dipole polarization, making a significantly contributing to electromagnetic wave attenuation. Increasing the Ni concentration drives the planar alignment of nanoparticles between MXene interlayers. This configuration reduced the in-plane magnetic anisotropy and its corresponding anisotropy field, facilitating in-plane magnetic domain rotation. Conversely, it enhances the out-of-plane magnetic anisotropy field, impeding out-of-plane domain rotation. The synergistic interplay between these anisotropic effects enables the material to break through the Snoek limit, substantially enhancing high-frequency complex permeability. However, excessive Ni loading exceeds the confinement capacity of the MXene layered structure, causing surface agglomeration that diminished magnetic loss performance, which is reflected in a decrease in the real part of permeability. At the optimal $\text{Ti}_3\text{AlC}_2\text{:NiCl}_2\cdot 6\text{H}_2\text{O}$ molar ratio of 1:3 (Fig. 5c), the composite achieved exceptional performance, a $RL_{\min}$ of -64.51 dB at a thickness of 1.98 mm, an EAB of 4.96 GHz, and an RCS reduction of -15.73 dB·m².

Wang et al. achieved the scalable preparation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene modified with Ni single atoms (Ni_1), sub-nanometer clusters (Ni_3), and nanoparticles (Ni_5) through precise control of precursor dosage, systematically investigating the influence of Ni microstructure on electromagnetic wave absorption properties [113]. As shown in Fig. 5d, the absorption performance exhibits a significant non-monotonic dependence on the dispersion state of Ni. The Ni single-atom modified Ni_1 -MXene demonstrated an RL of -32.2 dB at 1.5 mm thickness, with an EAB of 2.68 GHz. As the precursor

content increases and Ni aggregation intensifies, the Ni₂-MXene variant showed a lower *RL* of -39.85 dB at the same thickness, along with a broader EAB of 4.04 GHz. The Ni₃-MXene composite exhibits the optimal performance, achieves a *RL*_{min} of -54.0 dB at a thickness of 2.0 mm, with an EAB as wide as 6.8 GHz. This work confirms that the rational design of metal-anchored MXene can effectively enhance electromagnetic wave dissipation via electron localization induced by metal-support interactions. To clarify the underlying mechanism, density functional theory (DFT) calculations were performed to analyze the differential charge density and density of states across the different Ni-MXene systems (Fig. 5e). Ni₃-MXene displayed the highest total density of states at the Fermi level, demonstrating improved electron transition and dipole polarization capabilities. More importantly, cyano-bridged clusters in Ni₃-MXene induced pronounced charge localization, which strengthened interfacial polarization and electron-phonon interactions, thereby promoting electromagnetic wave dissipation. However, this localization concurrently restricted long-range electron migration, reducing the overall electrical conductivity. Furthermore, electronic coupling between the clusters and the MXene substrate constructs an asymmetric electron environment, generating permanent dipoles that significantly enhance dipole relaxation under alternating electromagnetic fields.

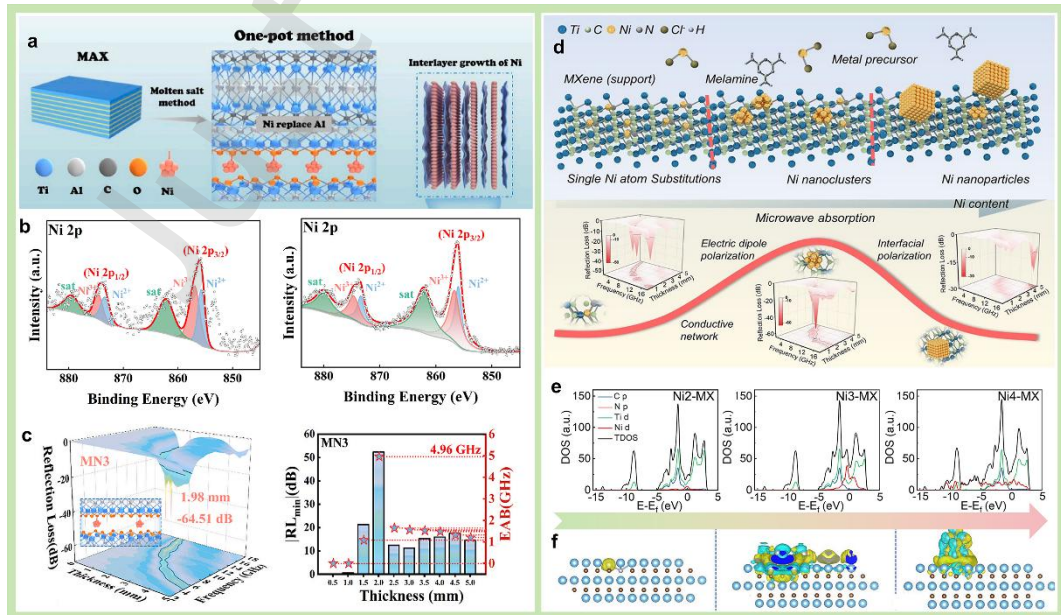


Figure 5 (a) Schematic diagram of the preparation process of Ti₃C₂T_x/Ni composite materials. (b) XPS peak fitting spectrum of Ni 2p in MN₃. (c) 3D *RL* diagram of sample MN₃ and the values of

$RL_{\min}$ and EAB at different matching thicknesses. Reproduced with permission from Ref. [112], © Elsevier Ltd. 2024. (d) Structural characterization of Ni-MX composites and 3D RL diagram. (e) Density of states of Ni_2 -MX, Ni_3 -MX, and Ni_4 -MX. (f) Differential charge density and its linear distribution of interatomic potential energy/density. Reproduced with permission from Ref. [113], © Springer 2025.

As illustrated in Fig. 6a, Wen's group innovatively constructed sea-urchin-like 3D PMMA@MXene@Ni architectures [114]. Multilayered $Ti_3C_2T_x$ MXene adhered to PMMA microspheres via hydrogen bonding, providing abundant active sites for the subsequent Ni nanospike growth. The captured Ni^{2+} ions were then in-situ reduced by hydrothermally treatment to form Ni nuclei. Driven by the surface energy anisotropy of Ni crystals, which follows the order of $\gamma_{(110)} > \gamma_{(100)} > \gamma_{(111)}$, Ni nanocrystals tend to grow preferentially along the $\gamma_{(111)}$ crystallographic planes following the minimum surface energy principle, eventually forming high-density, uniformly dispersed anisotropic Ni nanospikes (Fig. 6b). The introduction of Ni reduced the overall dielectric constant of the material. However, the 3D architecture enhances polarization capability while suppressing excessive MXene stacking, resulting in a higher high-frequency dielectric constant than 2D counterpart. Meanwhile, the PMMA@MXene@Ni microspheres were coated with an anisotropic, high-density shell composed of conical antenna-like Ni nanospikes. The entire sea-urchin-like unit generated abundant stray magnetic flux lines, confirming its strong magnetic character. These conical Ni nanospikes acted as magnetically activated antennas, which trigger intense magnetic flux release and exhibit significant magnetic coupling between adjacent nanospikes. As a result, at a matching thickness of 1.5 mm, this 3D material obtains an EAB of 4.48 GHz, and achieved a $RL_{\min}$ as low as -59.6 dB at 15.76 GHz (Fig. 6c).

Pan et al. (Fig. 6d) utilized magnetic-field-guided assembly to precisely organize micro/nano Ni particles into macroscopically aligned hair-like chains [116]. These were subsequently encapsulated within a bacterial cellulose/MXene aerogel matrix through oriented self-assembly engineering, forming banyan-fruit-inspired Bacterial Cellulose/MXene/Ni-chain Aerogels (BCMNA) [115]. Scanning electron microscopy (Fig. 6f) confirmed the homogeneous dispersion of nickel chains within the composite

framework, which exhibited both parallel and interwoven configurations. The intimate interparticle junctions and interchain magnetic interactions facilitated contactless energy transfer at microscopic scales. Macroscopic visualization distinctly revealed the highly aligned nanofibrous architecture, with individual Ni chains exceeding 1 cm in length. The enhanced Ni chain length intensified the coupling effects among these unidirectionally oriented 1D structures. Their characteristically low electrical percolation threshold endowed them with exceptional charge mobility and conductivity, which led to systematically elevated complex permittivity across the 2–18 GHz frequency range. Variations in magnetic phase drove the dynamic evolution of magnetic vortices, while interchain magnetic coupling networks significantly amplify magnetic dissipation (Fig. 6g). When synergistically combined with electromagnetic cooperative effects, this multifaceted mechanism ultimately results in breakthrough electromagnetic wave absorption performance. For the composite, a $RL_{\min}$ of -52.5 dB is obtained at a 1.75 mm, while the EAB reached 7.0 GHz at 2.05 mm matching thickness. Even at a thickness of 1 mm with increased Ni-chain loading, the material maintained significant absorption capability with an RL of -31.9 dB.

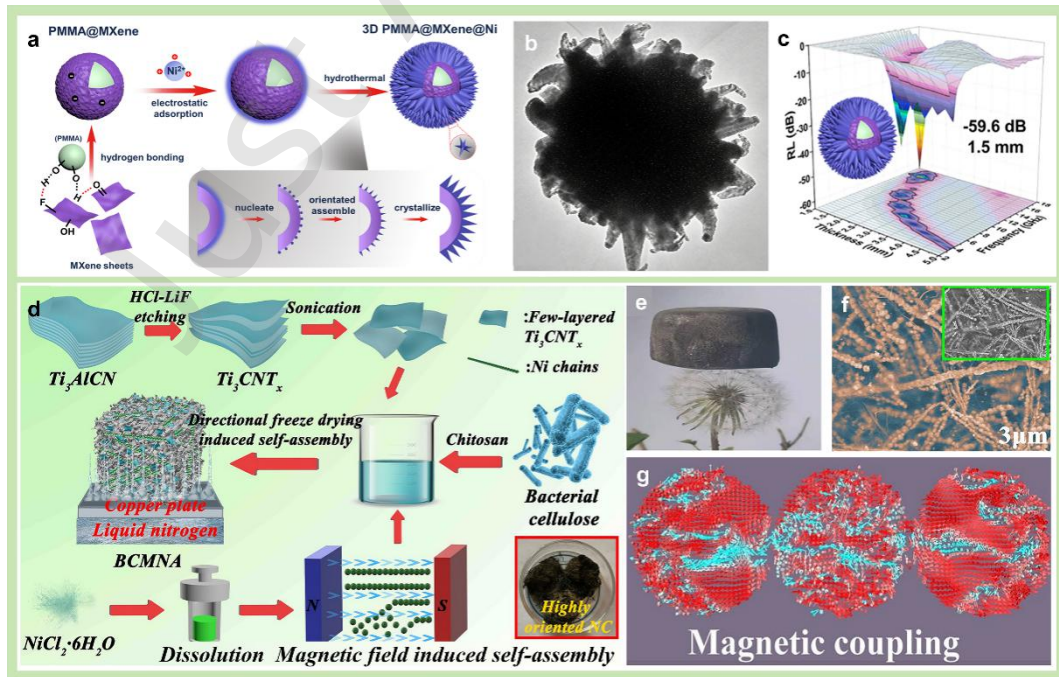


Figure 6 (a) Schematic diagram of the preparation process of 3D PMMA@MXene@Ni samples. (b) TEM images of 3D PMMA@MXene@Ni samples. (c) 3D diagram of frequency dependence

of 3D PMMA@MXene@Ni. Reproduced with permission from Ref. [114], © American Chemical Society 2021. (d) Schematic diagram of the preparation process of BCMNA samples. (e) Digital image of BCMNA samples standing on dandelions. (f) SEM images of Ni chains. (g) Micromagnetic simulation result of Ni chain. Reproduced with permission from Ref. [116], © Springer 2022.

The strategic integration of magnetic pure metals as functional phases leverages their inherent advantage of high M_s , thereby imparting a strong magnetic response to MXene-based composite systems. This incorporation establishes multiple magnetic loss pathways, predominantly governed by eddy current dissipation and supplemented by natural resonance and exchange resonance mechanisms. Distinct electromagnetic characteristics are observed among the three metals. Fe, distinguished by its lower cost and strong magnetic response, is the most widely adopted magnetic component for enhancing low-frequency microwave absorption. Co exhibits pronounced magnetocrystalline anisotropy, enabling it to maintain stable magnetic dissipation at high frequencies and contributing to the broadening of the EAB. Ni, with its moderate electrical resistivity and favorable oxidation resistance, optimizes high-frequency eddy current matching conditions while preventing excessive conductive loss.

3.2 Magnetic metal alloy-enhanced MXene MAMs

Magnetic metal alloys are a class of ferromagnetic nanomaterials that include elemental Fe, Co, Ni, their binary and ternary alloys, as well as certain manganese-based and rare-earth intermetallic compounds. A core advantage of these alloys is that key magnetic parameters including M_s , μ and H_c can be precisely tuned by rationally regulating chemical composition, crystal phase structure, and post-synthesis heat treatment protocols. Owing to this extraordinary tunability, magnetic alloys have become irreplaceable functional materials for modern electronics, power systems, and emerging clean energy technologies [117-119].

FeCo alloys are particularly notable for their exceptionally high M_s , reaching values as high as 240 emu g⁻¹, which exceed those of pure Fe and Co. This places them among the alloys with the highest known magnetic moments. The high M_s endows the composites with superior magnetic responsiveness and magnetic energy

density, leading to enhanced magnetic loss at lower frequencies. Furthermore, FeCo alloys possess an ultra-high T_c and substantial magnetocrystalline anisotropy. These properties not only allow effective tuning of the natural resonance frequency to maintain high permeability at high frequencies, but also ensure stable ferromagnetic behavior over a wide temperature range [120, 121]. Rao et al. fabricated $\text{Co}_7\text{Fe}_3@\text{C}/\text{Ti}_3\text{C}_2\text{T}_x$ nanocomposites successfully (Fig. 7a), effectively addressing the dual challenges of MXene nanosheet restacking and magnetic particle agglomeration [122]. In this hierarchical architecture, hollow $\text{Co}_7\text{Fe}_3@\text{C}$ nanospheres were uniformly wrapped by small $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets, while larger nanosheets acted as bridges to construct a 3D conductive network. The abundant heterogeneous interfaces between $\text{Ti}_3\text{C}_2\text{T}_x$ and $\text{Co}_7\text{Fe}_3@\text{C}$ triggered a pronounced nonlinear dielectric resonance effect, which induced conductive hysteresis and effectively optimized the complex permittivity of the composite. In another work, Li and colleagues synthesized FeCo powders with two distinct morphologies by precisely controlling the $\text{Fe}^{2+}/\text{Co}^{2+}$ molar ratio (Fig. 7b) [123]. A ratio of 5:1 produced sheet-like structures, while a ratio of 1:4 yielded flower-like morphologies. Magnetic characterization revealed that flower-like FeCo exhibited a significantly higher M_s (161.3 emu g^{-1}) compared to the sheet-like morphology (109.1 emu g^{-1}). This improvement is attributed to the larger specific surface area of the flower-like structure, which promotes greater magnetic moment ordering and strengthens magnetic coupling interactions. Furthermore, the numerous surface protrusions on the nanoflowers provide abundant sites for charge accumulation and active magnetic response, which is conducive to stronger dielectric loss and enhanced magnetic coupling. As shown in Fig. 7c, Wang et al. innovatively adopted an intercalation-induced growth and nucleation strategy to successfully fabricate MXene/CoFe@C composites [124]. This strategy effectively avoided the complex growth conditions required by conventional MXene intercalation methods, while simultaneously achieving the transition from hydrophilic to hydrophobic properties and endowing the composite with excellent corrosion resistance. By precisely adjusting the CoFe content and annealing temperature, a balance between attenuation capability and impedance matching was

achieved, leading to ultra-thin and broadband microwave absorption performance. Notably, the electromagnetic wave attenuation of this composite is mainly dominated by dielectric loss, which can be further divided into two components: approximately 75% of the total dielectric loss originates from conduction loss, while the remaining 25% comes from polarization relaxation loss. The excellent microwave absorption performance can be attributed to the synergistic interaction between multiple loss mechanisms (Fig. 7d). First, the 2D conductive network provided by MXene facilitates efficient electron transport, resulting in significant conduction loss. Furthermore, the annealing process not only effectively removes adsorbed water molecules intercalated between MXene layers, but also promotes the formation of a dense lamellar structure under the influence of spherical internal stress, which simultaneously consumes oxygen-containing functional groups on the $\text{Ti}_3\text{C}_2\text{T}_x$ surface and markedly delays its oxidation. Consequently, the oxidation temperature of $\text{Ti}_3\text{C}_2\text{T}_x$ under an argon atmosphere is remarkably elevated from 500°C to 900°C . Additionally, the introduced high-density oxygen vacancy defects can efficiently trap electrons, significantly enhancing dipole polarization. Thirdly, the uniform embedding of CoFe microspheres in the MXene interlayers creates abundant heterogeneous interfaces, which contributing to both interfacial polarization loss and enhanced conduction loss. Meanwhile, the CoFe particles introduce natural resonance and exchange resonance, which helps regulate the electromagnetic parameters of the composite and optimize impedance matching. Notably, the EAB gradually broadens with increase of CoFe content. Finally, the lamellar structure of MXene promotes multiple internal reflections of incident electromagnetic waves, which extends their propagation path and thereby enhancing absorption efficiency. Shu and collaborators innovatively combined bio-inspired multiscale pore engineering with freeze-drying self-assembly to construct $\text{FeCo@C/N-Ti}_3\text{C}_2\text{T}_x$ heterojunctions [125]. This strategy achieved atomic-level uniformity of N doping while effectively alleviating the restacking of MXene nanosheets. Crucially, precise Fermi level modulation can effectively improve the microwave absorption capability of the material. Through combined atomic-scale charge dynamics analysis and mesoscale DFT simulations

(Fig. 7e), the team clarified the optimization mechanism of electronic structure and energy conversion in N-doped MXene. Computational results revealed that N doping induces Fermi level displacement, with this shift and its concomitant built-in electric field enhancement constituting the fundamental driver for intensified interfacial polarization. Further density of states analysis revealed the interaction between metal and non-metal atoms, confirming the regulatory effect of N doping on the local magnetic environment. This electronic restructuring directly modulates magnetic dynamics, thereby fine-tuning magnetic loss performance. Among all tested samples, PM-1 achieved a $RL_{\min}$ of -58.65 dB, with an EAB of 4.56 GHz. As for sample PM-2, characterized by an ultralow bulk density of 9.8 mg cm^{-3} and high pore connectivity of $\kappa \approx 0.87$, can readily adhere to delicate surfaces like plant leaves, at a thickness of 2.30 mm, this sample reaches a $RL_{\min}$ of -67.05 dB, and its EAB reaches 3.24 GHz. Remarkably, with a low filler loading of only 15 wt.%, PM-4 still reaches a $RL_{\min}$ of -50.52 dB, while achieves an EAB as wide as 4.12 GHz, demonstrating its great application potential.

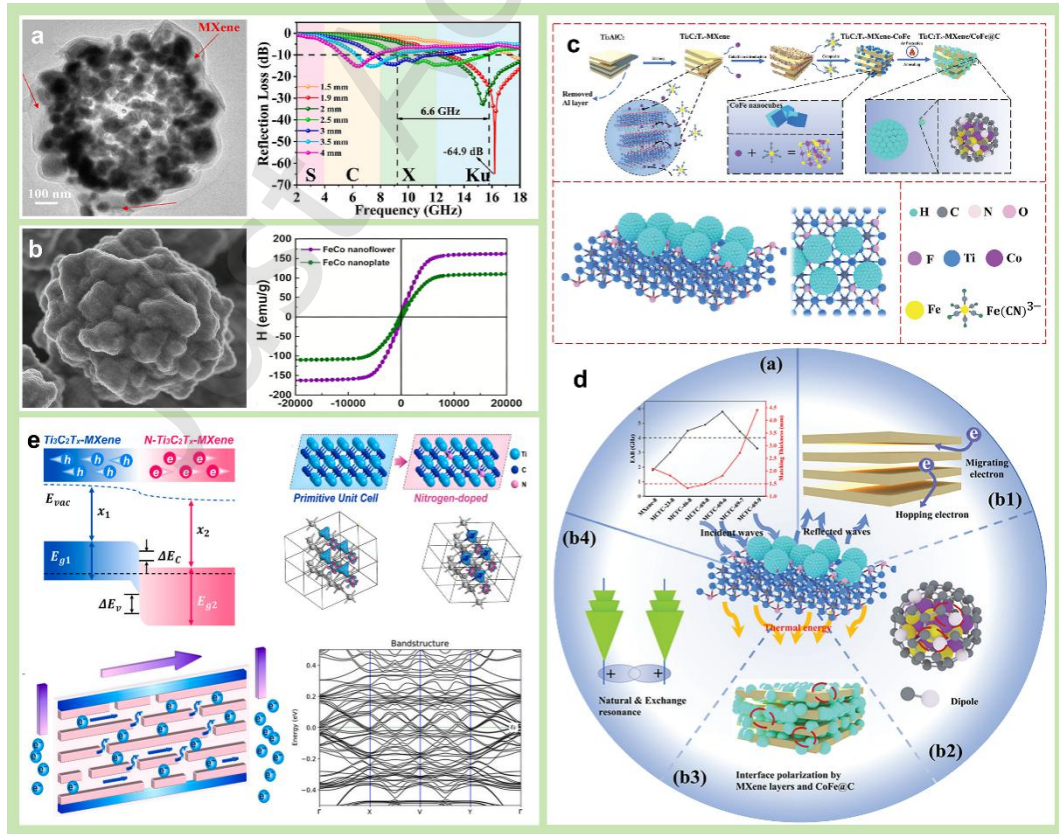


Figure 7 (a) TEM images and RL values of $\text{Co}_7\text{Fe}_3@\text{C}/\text{Ti}_3\text{C}_2\text{T}_x$. Reproduced with permission from Ref. [122], © Elsevier Ltd. 2024. (b) TEM images and magnetic hysteresis loops of nanoflower-like FeCo. Reproduced with permission from Ref. [123], © Elsevier Ltd. 2020. (c) Flow chart and structure diagram for the preparation of $\text{Ti}_3\text{C}_2\text{T}_x\text{-MXene/CoFe@C}$ sample. (d) Absorption mechanism diagram of $\text{Ti}_3\text{C}_2\text{T}_x\text{-MXene/CoFe@C}$ sample. Reproduced with permission from Ref. [124], © Wiley-VCH GmbH 2024. (e) Hole-electron recombination process under the Fermi level shift. Reproduced with permission from Ref. [125], © Elsevier B.V. 2025.

NiCo alloys present significant promise in bimetallic microwave absorption systems, owing to their cost-effective synthesis, robust structural stability, tunable magnetic properties, favorable impedance matching characteristics, and good environmental compatibility. These combined merits position them as highly competitive candidates for advanced electromagnetic wave absorption applications [126]. Gao and colleagues (Fig. 8a) engineered a composite system integrating flower-like NiCo-LDH with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets [127]. By systematically modulating the mass ratio of NiCo-LDH to MXene, they found that at low MXene loading, NiCo-LDH enveloped the MXene framework; as MXene content increased from 50% to 80%, the distinctive flower-like morphology progressively diminished, inducing a structural evolution from MXene encapsulation to interlayer confinement of NiCo-LDH within MXene sheets. The optimal 75 wt.% MXene exhibited uniformly dispersed NiCo-LDH constrained between MXene layers, generating abundant heterointerfaces. This configuration significantly enhanced electromagnetic wave attenuation through multiple internal reflections and scattering events, prolonging propagation paths and extending the interaction duration with active components. Consequently, this structure achieved a $RL_{\min}$ of -64.24 dB at 12.0 GHz with a matching thickness of 2.18 mm, and reaches a $EAB_{\max}$ of 4.48 GHz when the thickness is 2.00 mm thickness. Wu's group (Fig. 8b) pioneered the synthesis of CoNi-MOF derived magnetic porous carbon (CoNiMPC)@CNTs/MXene composites, which was achieved via a combined strategy of solution precipitation, thermal treatment and electrostatic self-assembly [129]. During calcination, CoNi-MOF-74 underwent a morphological transition from a lychee-like to a mulberry-like structure. Organic ligands' decomposition promoted $\text{Ni}^{2+}/\text{Co}^{2+}$ ions' reduction, and

simultaneously triggered the in-situ growth of CNTs with diameters of 20–40 nm. The formation of CNTs is proposed to follow a catalytic “tip-growth” mechanism [128]: magnetic CoNi nanoparticles act as catalysts, reacting with carbon atoms at elevated temperatures; carbon atoms subsequently assemble into graphene-like structures on the surface of catalyst, which then scroll into nanotubes, with the continuous supply of carbon propelling the elongation of the CNTs away from the metal particles. The resulting CoNiMPC@CNTs (designated as CNC) were subsequently wrapped by MXene nanosheets via electrostatic interactions. Inspired by layer-pillar-layer architectures, Wang et al. anchored N-doped CNTs (NCNTs) onto multilayered $\text{Ti}_3\text{C}_2\text{T}_x$ MXene [131]. Their synthesis methodology comprised several key steps [130]: First, uniform nanosheet arrays were coated on MXene surfaces and edges to establish self-catalytic conversion sites. Subsequently, melamine was decomposed at low temperatures into C_3N_4 intermediates, which further fragmented into gaseous C_xN_y species (e.g., C_2N_2^+ , C_3N_2^+ , C_3N_3^+) upon heating. These fragments were adsorbed onto reduced CoNi alloy nanoparticles via 3d electron interactions. Finally, a thermodynamically driven rearrangement of carbon atoms, with selective nitrogen incorporation into the carbon lattice, yielded vertically aligned NCNTs. By regulating the melamine content, the length and density of the nanotubes could be controlled, thereby optimizing the microstructure and dielectric properties (Fig.8c). Increased melamine loading proliferated heterointerfaces, intensifying interfacial polarization relaxation while introducing abundant dipole defects. Simultaneously, the expansion of NCNTs widened the MXene interlayer spacing, effectively suppressing nanosheet restacking and facilitating unique 3D conductive network’s formation. XPS analysis revealed a positive shift in the Ti–C binding energy, confirming strong interfacial interactions that promoted electron transfer from MXene nanosheets to the NCNT frameworks. Crucially, while excessive nanotube growth increased the material density, an optimal interlayer gap created multiple reflection and scattering sites. This design not only prolonged electromagnetic wave propagation path, but also improved impedance matching (Fig. 8d and e). Consequently, the optimized absorber achieved exceptional performance, with a $RL_{\min}$ of -55.8 dB and a wide EAB of 5.88

GHz.

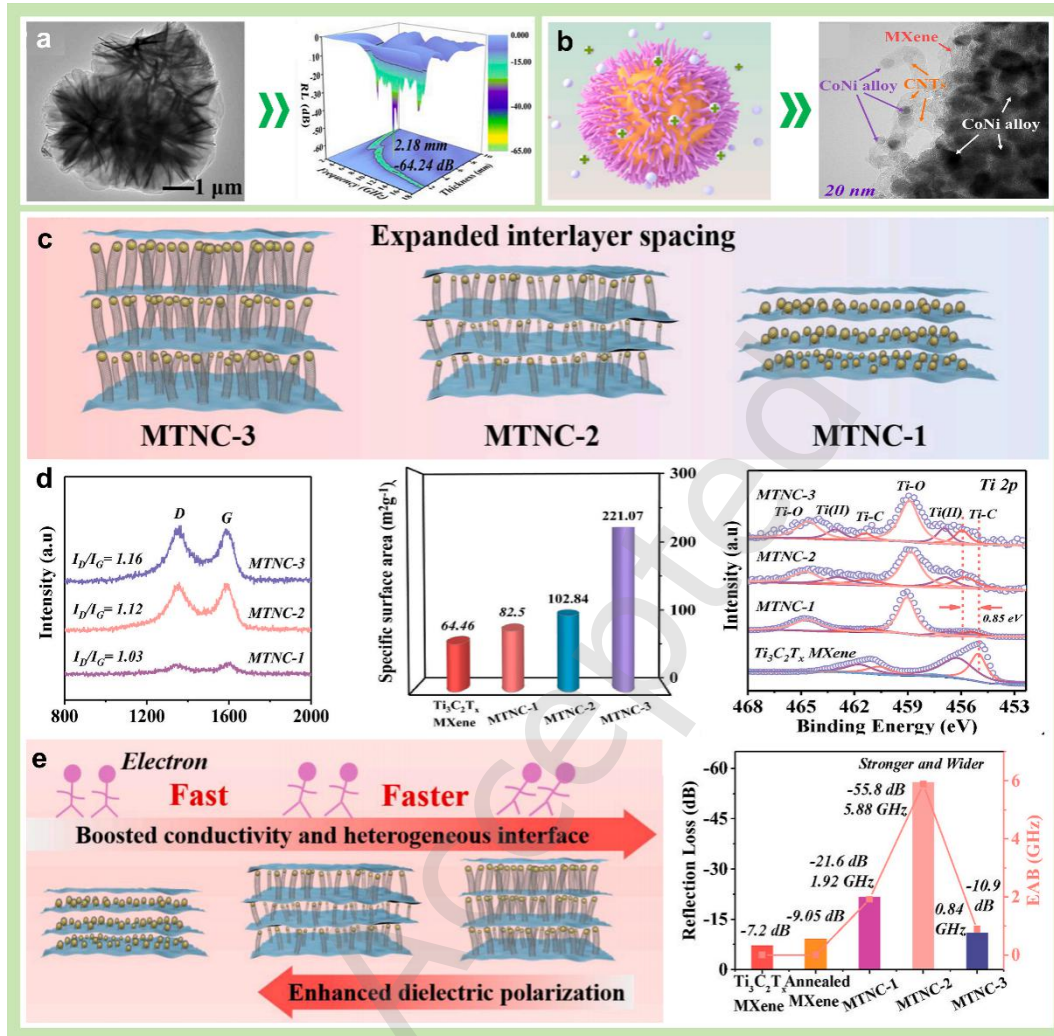


Figure 8 (a) TEM images of NiCo-LDH/MXene and 3D schematic diagram of RL values. Reproduced with permission from Ref. [127], © Elsevier B.V. 2021. (b) Schematic diagram of the structure of CNM composite material and TEM image. Reproduced with permission from Ref. [129], © Elsevier B.V. 2023. (c) Schematic diagrams of the morphological evolution of different MTNC composites. (d) Raman spectra, specific surface areas, and Ti 2p energy spectra of different MTNC samples. (e) Schematic diagrams of dielectric loss of different MTNC composites, RL values and EAB corresponding to different thicknesses. Reproduced with permission from Ref. [131], © Elsevier Ltd. 2023.

Zeng's group engineered MXene nanoribbons (NRs) via potassium hydroxide-assisted alkaline exfoliation, and constructing a hierarchical 0D/1D/2D MXene NRs-NiCo@NC network [132]. Initially, the Al layer in the Ti₃AlC₂ precursor was etched to obtain layered Ti₃C₂T_x MXene. Subsequent KOH intercalation induced shear-driven layer expansion, exfoliating the stacked MXene into interconnected nanoribbon networks with abundant microporous channels.

Ultrathin NiCo-LDH nanosheets were then uniformly anchored onto the MXene NR frameworks via hydrothermal growth, establishing intimate interfacial contact. After high-temperature heat treatment, the NiCo-LDH underwent dehydration and shrinkage to generate pores, and was in-situ into NiCo nanoparticles with an average size of approximately 11 nm. The surface of these nanoparticles is uniformly coated with a multilayer N-doped carbon “armor” (NiCo@NC) about 1.4 nm thick. This carbon coating not only prevents the magnetic NiCo nanoparticles from oxidation, but also mitigates their detachment from the conductive MXene substrate. Magnetic property analysis revealed that NiCo@NC exhibited a broad natural resonance peak in the 2–12 GHz frequency range, while the MXene nanoribbons showed a significant exchange resonance peak is located within 12–18 GHz. The composite material thus combines both resonance characteristics. Within the 14–18 GHz range, exchange resonance dominates the attenuation process, whereas eddy current loss is the predominant dissipation mechanism at lower frequencies and other bands. Based on the wave absorption mechanism depicted in Fig. 9a, this 0D/1D/2D hierarchical network achieves a $RL_{\min}$ of -57.1 dB at a matching thickness of 4.82 mm. Notably, it still maintains a strong absorption of -33.19 dB even at a reduced thickness of only 1.4 mm (Fig. 9b).

NiFe alloys, commonly designated as Permalloy, exhibit high permeability, low H_c , and high M_s . To overcome their limitations at GHz frequencies arising from the skin effect and the Snoek limit constraints, a mainstream strategy is to nanostructure Permalloy into flakes, fibers, or nanoparticles, and composite them with dielectric loss materials such as MXene or carbon-based matrices. This approach effectively broadens the EAB while achieving a synergistic magnetic-dielectric loss mechanism [133]. Lin et al. constructed an ultralight MXene/C composite aerogel embedded with Ni_3Fe micro-helical chains via a magnetic field-assisted polymerization-induced self-assembly strategy (Fig. 9c) [134]. Initially, Ni_3Fe nanoparticles were assembled into unique 1D chiral micro-helical chains through an ethylene glycol-based polyol reaction. Subsequently, the surfaces of these chains were wrapped with MXene nanosheets, and after encapsulation with poly-Schiff-base gel and subsequent

calcination, the final $\text{TiO}_2/\text{Ni}_3\text{Fe}/\text{MXene}/\text{C}$ quaternary aerogel was obtained. This multilevel structure design not only effectively suppress MXene nanosheets' stacking, but also integrates the magnetic-dielectric dual loss mechanism. Specifically, the 1D Ni_3Fe helical chains provide strong magnetic loss via an enhanced magnetic coupling effect, while the MXene/C conductive skeleton contributes excellent dielectric loss. As a result, the aerogel achieves a $RL_{\min}$ of -61.6 dB at a thickness of 3.0 mm with an ultralow filler loading of only 7.6 wt.%, and its EAB reaches 8.16 GHz at a thickness of 2.77 mm.

To address the bandwidth limitations of single-component Permalloy absorbers, researchers have developed FeCoNi ternary magnetic alloys. By precisely tuning the elemental composition, these alloys effectively combine the individual advantages of Fe, Co, and Ni: they maintain high permeability while shifting the natural resonance frequency to higher bands, thus partially breaking through the Snoek limit. This makes FeCoNi ternary alloys with great potential to develop high-performance broadband microwave-absorbing magnetic devices for practical applications. Li's group synthesized three batches of $\text{Ti}_3\text{C}_2\text{T}_x@\text{nano-Fe}_1\text{Co}_{0.8}\text{Ni}_1$ composites with different MXene contents via in-situ liquid-phase deposition [135]. Face-centered cubic spherical $\text{Fe}_1\text{Co}_{0.8}\text{Ni}_1$ nanoparticles were uniformly dispersed on the multilayered MXene's surface, exhibiting excellent dispersion without obvious agglomeration. With increasing MXene content, the composite exhibited typical soft magnetic properties, while both M_s and H_c show a trend of initial decrease followed by a subsequent increase. Meanwhile, the real and imaginary parts of the complex permittivity progressively increased, whereas those of the complex permeability gradually decreased. This led to increased attenuation constants but impaired impedance matching, consequently raising the $RL_{\min}$ and reducing the $\text{EAB}_{\max}$. For the composite with 90 mg MXene loading, a $RL_{\min}$ of -46.9 dB was realized at 1.1 mm absorber thickness, while the $\text{EAB}_{\max}$ reached 3.60 GHz when the thickness was adjusted to 1.0 mm. Notably, after introducing MXene, the optimal thickness corresponding to the maximum absorption bandwidth decreased from 1.5 mm to 1.0 mm, representing a significant 50% thickness reduction.

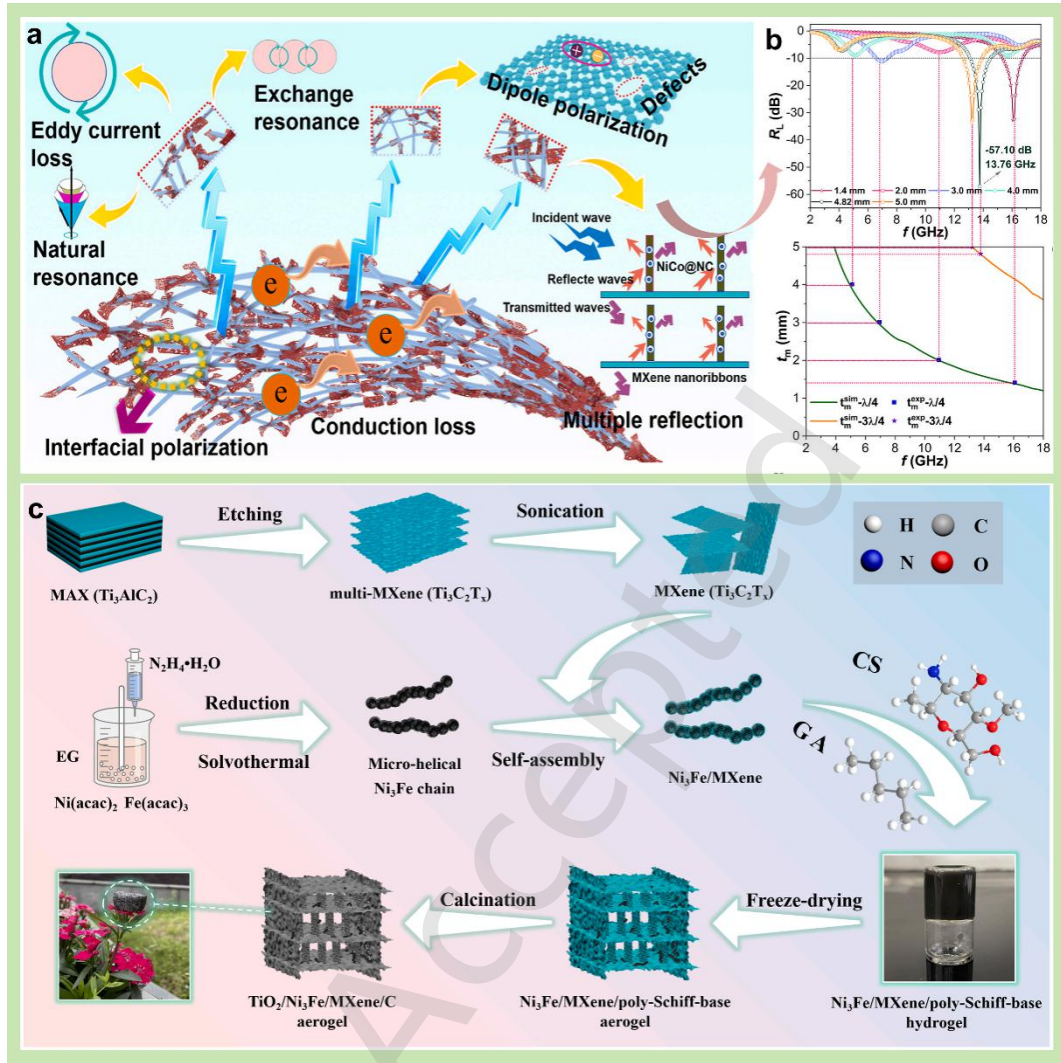


Figure 9 (a) Schematic diagram of the EMW absorption mechanism of MXene nanoribbons-NiCo@NC. (b) 2D RL values and simulation of t_m vs. f_m curves for MXene nanoribbons-NiCo@NC. Reproduced with permission from Ref. [132], © Elsevier Ltd. 2022. (c) Schematic diagram of the preparation process of NFMC aerogel. Reproduced with permission from Ref. [134], © Elsevier B.V. 2024.

Compared with pure metals, metal alloys offer a fundamental advantage in compositional tunability. By strategically adjusting alloy ratios, an optimal balance between M_s and magnetocrystalline anisotropy can be achieved, which allows precise regulation of the resonance frequency and effectively expands the EAB. Different alloy systems exhibit unique frequency response characteristics. FeCo binary alloys maintain high M_s and shift the natural resonance frequency to higher frequency bands, thus excelling superior high-frequency microwave absorption performance. FeNi binary alloys possess high permeability but are subject to more severe limitations

from the Snoek limit. FeCoNi ternary alloys are particularly suitable for constructing broadband absorption and applications under extreme conditions. Furthermore, compared with pure metal nanoparticles, metal alloy nanoparticles have better interfacial compatibility with MXene. Their surfaces provide richer coordination sites, which can form stronger coordination interactions with the terminal functional groups on MXene, significantly improving the structural stability of the composites.

3.3 Magnetic metal oxide-enhanced MXene MAMs

3.3.1 Iron oxides

The magnetism of spinel ferrites (AB_2O_4) stems from the antiparallel arrangement of magnetic moments of cations occupying the tetrahedral (A) and octahedral (B) sublattices. The magnitude and direction of the net magnetic moment are directly determined by cation distribution (normal, inverse, or mixed spinel), which provides great flexibility for tuning magnetic loss capability through compositional design. Furthermore, the high intrinsic electrical resistivity of spinel ferrites can effectively suppress eddy current loss at high frequencies and improve the impedance matching characteristic of absorbers. Nevertheless, ferrite/MXene composites' electromagnetic wave absorption mechanism varies greatly depending on whether the ferrite component is soft magnetic or hard magnetic [136].

Cobalt ferrite ($CoFe_2O_4$), a typical hard-magnetic material, is characterized by high M_s , large H_c , and high magnetocrystalline anisotropy constant. Tian et al. synthesized spherical $CoFe_2O_4/Ti_3C_2T_x$ MXene composites via a high-temperature solvothermal method [137]. Their study revealed that increasing the $CoFe_2O_4$ content expanded the interlayer spacing of the MXene and enhanced the interfacial magnetocrystalline anisotropy. When the $CoFe_2O_4$ content reached 80 wt.%, the composite achieved optimal performance, exhibiting a RL_{min} of -77.2 dB at 8.0 GHz with a matching thickness of 2.6 mm. As shown in Fig. 10a, Wang's group fabricated flexible PVDF/ $Ti_3C_2T_x$ /h- $CoFe_2O_4$ (c-PMHC) composite films with a layered porous electromagnetic gradient structures using a sequential doctor-blading technique [138]. The film exhibited a distinct three-layer stacked architecture (Fig.10b). The bottom

layer was a dense, smooth and highly oriented MXene layer induced by the shear force during doctor-blading, where nanosheets were regularly stacked to form continuous conductive channels. The middle and top layers are formed through vapor-induced phase separation and solvent displacement, constructing an interconnected porous network with a maximum porosity of 75.84%. This porous structure, combined with the hollow cavity structure of h-CoFe₂O₄, significantly reduces the density of the composite while synergistically optimizing impedance matching. Furthermore, the material exhibited typical gradient characteristics in elemental distribution, filler loading and electromagnetic properties. Functional elements such as Co, Fe, and Ti exhibit a gradient distribution along the thickness direction, leading to a gradual change in the conductivity and M_s of the composite film from the bottom to the top layer. Tight interfacial bonding between layers was achieved through solvent penetration, and abundant heterogeneous interfaces were formed between MXene nanosheets and hollow cobalt ferrite particles. The synergistic effect derived from this delicate multi-scale structural design not only provided multiple reflection and scattering paths, but also enhanced the combined contributions of interfacial polarization, conduction loss and magnetic loss. Moreover, this hierarchical structural construction also imparts the composite film with impressive structural stability and mechanical flexibility. Accordingly, the c-PMHC composite film demonstrated exceptional electromagnetic wave absorption capability (Fig. 10c), it delivers a $RL_{\min}$ of -54.4 dB at a matching thickness of 2.85 mm, and obtains an $EAB_{\max}$ of 5.9 GHz at a reduced thickness of 1.4 mm.

Magnetite (Fe₃O₄), with its inverse spinel structure, enables efficient electron hopping between Fe²⁺ and Fe³⁺ ions at the octahedral sites. This feature endows Fe₃O₄ with higher electrical conductivity compared to other ferrites materials, leads to a unique dielectric-magnetic dual-loss mechanism for electromagnetic attenuation [139-141]. Li et al. fabricated Fe₃O₄/C/MXene composites by combining MIL-101(Fe)-derived Fe₃O₄/C octahedral nanoparticles with few-layer MXene nanosheets [142]. The few-layer MXene retains its typical transparent wrinkled sheet morphology, while well-faceted octahedral Fe₃O₄/C nanoparticles were uniformly

anchored on the MXene surfaces. The incorporation of Fe_3O_4 effectively compensates for the inherent magnetic loss deficiency of pure MXene. The composite establishes a multi-band magnetic loss mechanism, which involves natural resonance at low frequency, exchange resonance at mid-to-high-frequency, and eddy current loss at high frequency, this mechanism is confirmed by the distinct resonance peaks observed in the complex permeability curves. Benefiting from this dielectric-magnetic synergy, the composite achieved a $RL_{\min}$ of -66.9 dB when the matching thickness is 3.2 mm, while the EAB can reach 10.7 GHz when the thickness is adjusted to 2.5 mm. As depicted in Fig. 10e, Cui's research team employed ultrasonic spray technology to control droplet size, inducing reduced graphene oxide (RGO) and MXene 2D nanosheets to self-assemble via interlayer forces into tightly stacked structures [143]. Via this fabricated process, crumpled composite microspheres of 6 μm diameter were obtained, named as RGO/MXene/ Fe_3O_4 (FMCM). In this hierarchical microsphere structure, Fe_3O_4 nanoparticles can be evenly distributed and firmly fixed onto the RGO and MXene frameworks, forming a unique "magnetic-insulating" network that effectively suppresses the agglomeration of magnetic nanoparticles (Fig. 10f). When the filler loading is as low as 40 wt.%, the researchers investigated the influence of RGO/MXene mass ratios on the electromagnetic parameters. Experimental results indicate that the RGO/MXene ratio of 4:1 achieved the optimal impedance matching, resulting in a $RL_{\min}$ of -44.2 dB at 14.2 GHz at an ultrathin thickness of only 1.2 mm. Based on this optimal binary ratio, the further incorporation of Fe_3O_4 nanoparticles additionally enhanced the electromagnetic attenuation capacity of the composite. Notably, since the microsphere diameter is primarily determined by the size of the sprayed droplets, the addition of Fe_3O_4 nanoparticles did not change the overall particle size of the FMCM microspheres. However, it significantly increased the degree and density of surface crumpling, which providing more active sites for magnetic particle attachment and heterogeneous interface construction. As the Fe_3O_4 doping content increased, both the characteristic impedance and the $RL_{\min}$ of the composite exhibited an initial increase followed by subsequent decrease. When the mass of Fe_3O_4 was 0.8 times the total mass of MXene and RGO, the FMCM

composite achieved a $RL_{\min}$ of -51.2 dB at 11.1 GHz with a matching thickness of 2.9 mm, and its EAB in the low-frequency range was extended to 4.7 GHz.

Ni^{2+} exhibits a strong preference for octahedral sites. Consequently, nickel ferrite ($NiFe_2O_4$), analogous to magnetite, adopts an inverse spinel structure in which Ni^{2+} ions and half of the Fe^{3+} ions occupy the octahedral sites, while the remaining Fe^{3+} ions are distributed the tetrahedral sites. As a typical soft magnetic material, it possesses moderate M_s and T_c [144]. Yuan's group innovatively introduced SiO_2 as an electromagnetically transparent buffer layer between the magnetic core and MXene nanosheets, constructing a sandwich-structured, interlayer-engineered $NiFe_2O_4@SiO_2@MXene$ (NSM) hierarchical composite [145]. The intrinsically low dielectric constant and high transparency of this intermediate buffer layer fulfill multiple functions: First, it mitigates the specular reflection caused by MXene's inherently high electrical conductivity, synergistically modulating the system's electromagnetic parameters and optimizing impedance matching. Second, it acts as a compact physical barrier, isolating the magnetic core from air and moisture to inhibit oxidative degradation. Third, it enhances interfacial compatibility between components, preventing particle agglomeration and uneven distribution common in direct composites systems, thus fundamentally addressing the issue of localized impedance mismatch. Furthermore, this unique architecture introduces abundant heterogeneous interfaces that induce strong interfacial polarization relaxation. The continuous network conductive by 2D MXene nanosheets provides substantial conduction loss, while the magnetic components contribute multiple magnetic loss mechanisms, including natural resonance and eddy-current loss. Benefiting from the synergistic effect of these three components, the NSM composite exhibits excellent comprehensive electromagnetic wave absorption performance, achieving a $RL_{\min}$ of -52.8 dB at a matching thickness of 2 mm. Notably, the NSM-4 sample, with an ultrathin thickness of only 1.5 mm, attained an EAB of 7.2 GHz, sufficient to cover the entire Ku-band.

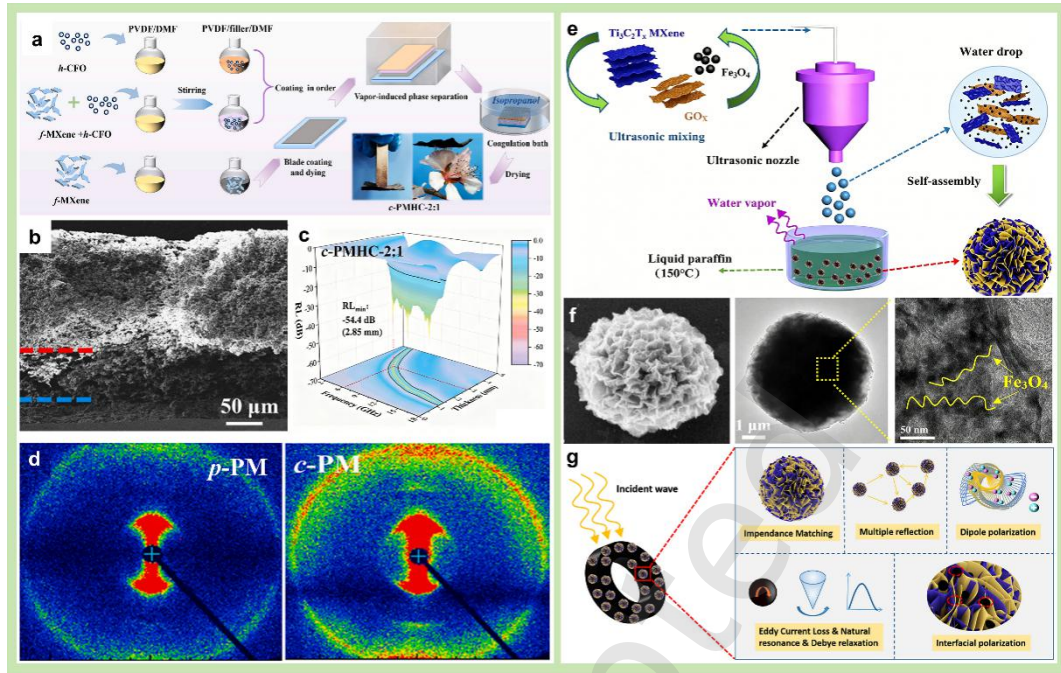


Figure 10 (a) Preparation route of *c*-PMHC-2:1 composite film sample. (b) SEM images of the cross-section of *c*-PMHC-2:1 composite. (c) 3D reflection loss curve of *c*-PMHC-2:1 composite material. (d) The WAXS patterns of *c*-PM, and *p*-PM. Reproduced with permission from Ref. [138], © Elsevier B.V. 2025. (e) Schematic diagram of the preparation route for FMCM samples. (f) SEM images and TEM images of FMCM samples. (g) Microwave absorption mechanism of FMCM samples. Reproduced with permission from Ref. [143], © Elsevier Ltd. 2020.

Zinc ferrite (ZnFe_2O_4) typically adopts a normal spinel structure, in which non-magnetic Zn^{2+} ions occupy the A sites, rendering the A-sublattice magnetically inactive. However, experimentally synthesized nanoscale ZnFe_2O_4 often exhibits weak ferrimagnetism and semiconducting behavior, which is due to incomplete cationic ordering [146]. As illustrated in Fig. 11a, Xu's team developed a water-induced self-assembly strategy for constructing 3D hierarchical magnetic nanocrystal@C@MXene (ZFCM) composites [147]. The core of this method relies on utilizing an aqueous environment to induce surface activation between MXene and metal-glycerolate (M-G) precursors. By regulating the MXene loading, the optimal sample ZFCM-7, featuring a microscale 3D hierarchical network, demonstrated optimal performance. With an ultrathin thickness of only 1.33 mm, it achieved an outstanding $RL_{\min}$ of -62.59 dB at the frequency of 14.16 GHz, and the corresponding EAB reached 4.42 GHz. To elucidate the influence of the 3D hierarchical architecture on absorption performance, Xu et al. comparatively analyzed the electromagnetic

field distributions of pristine 3D MXene and ZFCM-7 (Fig. 11b). For pure MXene, the inherent hollow cavities cause localized electric field concentration. In contrast, ZFCM-7 induced significant interfacial electric field distortion and energy localization due to its abundant heterogeneous interfaces, directly confirming a strong interfacial polarization effect. Magnetic loss distribution simulations further revealed that ZFCM-7 exhibited a dispersed yet high-energy-density magnetic loss profile, significantly surpassing that of pure MXene. This performance enhancement is attributed to its engineered magnetic coupling network. Carbon encapsulation not only suppressed the agglomeration of magnetic nanocrystals, increasing the number of effective magnetic moments, but also promoted the oriented alignment and exchange coupling of these moments. Simultaneously, the high dispersion of magnetic nanocrystals within the carbon matrix effectively blocked continuous conductive pathways, reduced eddy-current loops, and attenuated the skin effect, ultimately enhanced the overall magnetic interactions.

Ferric oxide, commonly known as hematite (α -Fe₂O₃), possesses a corundum-type hexagonal crystal structure and is generally classifying as a weak dielectric loss material. At room temperature, it exhibits weak ferromagnetism due to non-collinear spin arrangements [148]. When composited with highly conductive MXenes, the additional magnetic loss contribution significantly enhances the overall electromagnetic wave absorption performance. As depicted in Fig. 11c, Chen's team employed a green γ -radiation method to in-situ synthesis of nano-oxide intercalated MXene composites [149]. Initially, the negatively charged functional groups on the MXene surface first anchor metal cations through electrostatic interactions. Upon exposure to ionizing radiation, water molecules in the aqueous system decompose to generate various active free radicals. When isopropanol is introduced as a $\cdot$ OH scavenger, the generated $\cdot$ CH₂C(OH)CH₃ radicals exhibit reductive properties. These species reduce metal ions to lower valence states or to zero valence (e.g., Fe³⁺ to Fe⁰, Cu²⁺ to Cu⁺). Subsequently, Fe⁰ is oxidized by reactive oxygen species in the system to form Fe₂O₃, while unstable CuOH decomposes into CuO during the irradiation-drying process. Throughout the whole process, reduction-oxidation

reactions of metal ions occur on the MXene flake surfaces, resulting in the final metal oxide nanoparticles being distributed between the MXene nanosheets. This method yields a high specific surface area and abundant active sites, enabling highly uniform dispersion and effectively avoiding oxide agglomeration common in traditional approaches. It represents a facile and green preparation method suitable for large-scale production, where the reductive environment at room temperature effectively prevents MXene oxidation. Research results indicate that this unique intercalated structure significantly enhances the wave absorption performance. The $\text{Fe}_2\text{O}_3/\text{MXene}$ composite achieved a $RL_{\min}$ of -58.7 dB at a thickness of 2.35 mm, while the CuO/MXene composite exhibited a $RL_{\min}$ of -50.9 dB at 2.55 mm thickness and an EAB of 4.88 GHz at 1.3 mm thickness. Furthermore, Huang et al. synthesized spindle-shaped $\alpha\text{-Fe}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x$ composites using spindle-shaped MIL-88A as a precursor, facilitated by KOH pre-treatment followed by annealing and oxidation (Fig. 11d) [150]. Their investigation revealed that direct annealing in air led to structural collapse of the precursor due to an excessively fast reaction rate. In contrast, precursors subjected to KOH pre-treatment maintained a complete spindle-shaped morphology. Importantly, the $\alpha\text{-Fe}_2\text{O}_3$ obtained with KOH treatment exhibited slightly higher dielectric constant and magnetic permeability. The $\alpha\text{-Fe}_2\text{O}_3/\text{Ti}_3\text{C}_2\text{T}_x$ system achieved the best impedance matching performance when the mass ratio between the two components was controlled at 1:3, it delivered a $RL_{\min}$ of -34 dB at 3.0 mm thickness. When the matching thickness was further reduced to 1.5 mm, the EAB increased to 2.8 GHz.

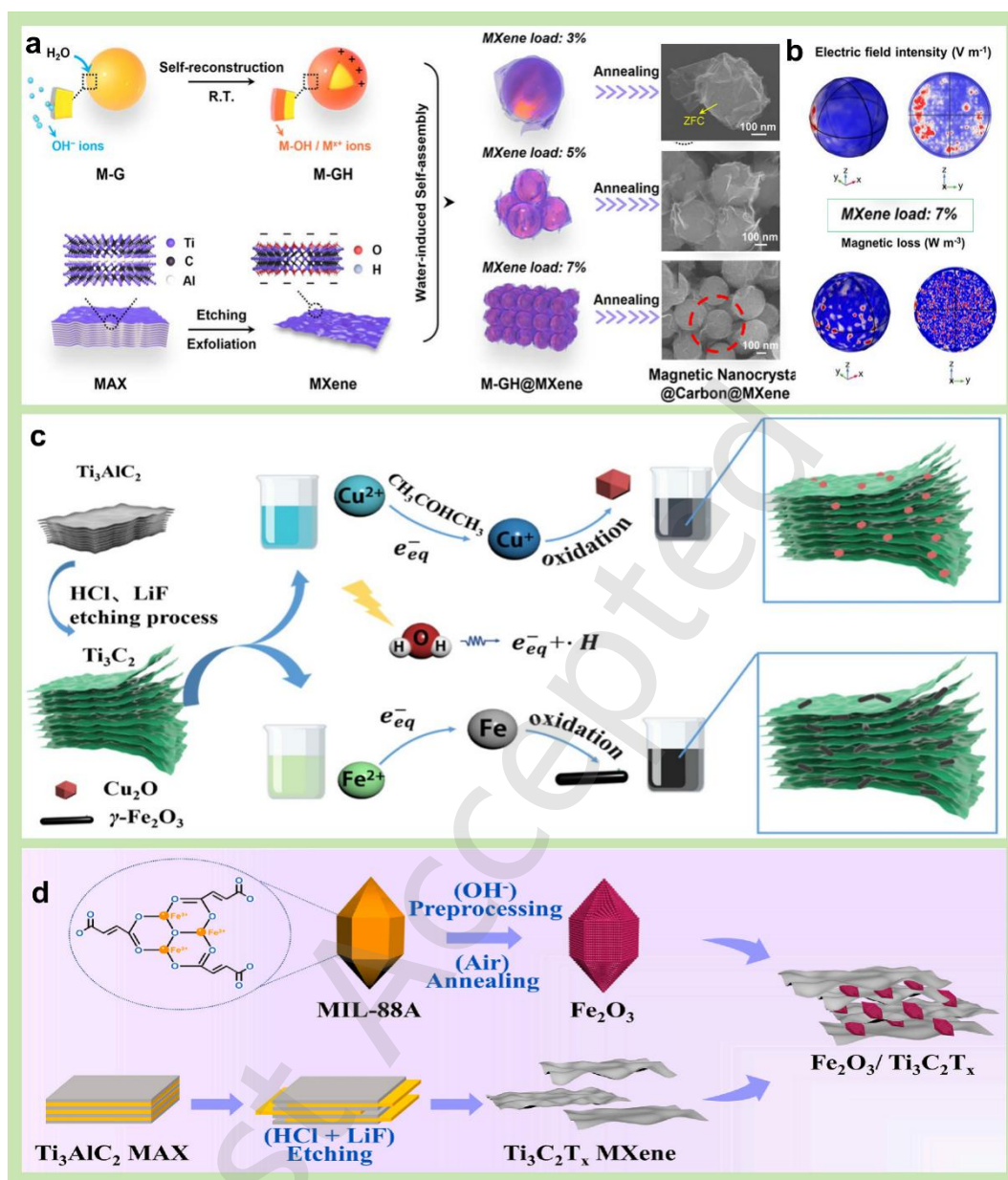


Figure 11 (a) Schematic diagram of the preparation of different ZFCM samples. (b) Electric field intensity distribution and magnetic loss distribution of ZFCM samples. Reproduced with permission from Ref. [147], © The Royal Society of Chemistry 2023. (c) Schematic diagram of the preparation process of composite materials. Reproduced with permission from Ref. [149], © IOP Publishing Ltd. 2023. (d) Preparation route of Fe₂O₃/Ti₃C₂T_x composites. Reproduced with permission from Ref. [150], © Elsevier Ltd. 2024.

3.3.2 Cobalt oxides

Cobalt oxides exhibit diverse crystal structures and physicochemical properties, which arise from the variable valence states of cobalt. Owing to their unique structural characteristics, cobalt oxides have found widespread applications in multiple research fields, including electrochemical energy storage, catalysis, sensing, and magnetic

nanomaterials. The three most common studied cobalt oxide crystal structures correspond to CoO (cobalt (II) oxide), Co₃O₄ (cobalt (II, III) oxide), and Co₂O₃ (cobalt (III) oxide) [151].

Cobalt (II) oxide (CoO) is a rock-salt (NaCl-type) antiferromagnetic material, in where Co²⁺ and O²⁻ occupy octahedral sites in an FCC lattice to form a close-packed structure. Due to surface, size, and defect effects, CoO nanoparticles often exhibit weak ferromagnetism [152]. As shown in Fig. 12a, Zhang's team proposed an ingenious strategy that uses negatively charged MXene nanosheets as both structural directing agents and supporting substrates to achieve the interlaced growth of ultrathin CoO nanosheets and core-shell Co@C nanoparticles [153]. This dual-magnetic-phase architecture enhances magnetic coupling, thereby improving the overall permeability of the composite absorber. By tuning the addition amount of MXene, a series of composite absorbers in magnetic phase content, which were labelled as L-/M-/H-CoO/Co@C/MX corresponding to low, medium, and high content respectively, were prepared in this work. The synthesis follows a two-step mechanism. Initially, staggered ZIF-67 nanocrystals and Co(OH)₂ nanosheets were co-assembled on the MXene surface through simultaneous adsorption, hydrolysis, and coordination of Co²⁺ ions. Subsequent pyrolysis in H₂/Ar atmosphere reduced Co(OH)₂ nanosheets to magnetic CoO nanosheets in-situ, and converted ZIF-67 nanocrystals into core-shell Co@C nanoparticles intercalated between CoO nanosheets. In the L-CoO/Co@C/MX sample, magnetic nanoparticles and nanosheets are sparsely distributed, which is insufficient to provide sufficient magnetic loss. In H-CoO/Co@C/MX, excessive magnetic phase loading induces stacking and restacking of the surface CoO nanosheets. In contrast, M-CoO/Co@C/MX with moderate magnetic phase content achieved a EAB_{max} of 5.6 GHz covering 12.4–18.0 GHz at a thin thickness of 1.8 mm, and achieved a RL_{min} of -73.4 dB when the thickness was 2.1 mm. As shown in Fig. 12b, Yu et al. introduced large anionic MoO₄²⁻ into a ZIF-67 template to derive a CoMo-LDH, which was then composited with MXene to construct a 3D hierarchical framework (MXene@CoMo-LDH) [154]. After annealing treatment, the mechanically fragile CoMo-LDH transformed into a

mixed transition metal oxide (TMOs) system composed of CoO/Co₂Mo₃O₈, yielding the final MXene@TMOs composite. Due to MXene and CoMo-LDH possess opposite surface charge properties, effective electrostatic self-assembly can only be driven at a mass ratio of 1:1. Deviation from this optimal ratio led to structural instability: excessive MXene content imposes excessive stress on CoMo-LDH during the subsequent conversion to TMOs, causing fracture; conversely, excessive CoMo-LDH content resulted in a brittle shell cannot provide effective structural support, leading to the collapse of the worm-like architecture. Furthermore, annealing treatment was crucial for performance enhancement. Without annealing at the optimal 1:1 doping ratio, the 3D conductive network cannot be fully developed, and the electromagnetic wave absorption mechanisms were incomplete. As a result, the material requires an impractical thickness of 7.8 mm and a narrow EAB of 2.8 GHz, which cannot meet practical requirements. After annealing, the MXene@TMOs sample exhibited significantly optimized impedance matching, achieved remarkable lightweight and thinness, and demonstrated the most satisfactory electromagnetic wave absorption performance, the RL_{min} reached -50.30 dB, and the EAB_{max} was 5.12 GHz.

Cobalt (II, III) oxide (Co₃O₄), the most thermodynamically stable cobalt oxide, adopts a normal spinel crystal structure and exhibits excellent structural stability at elevated temperatures, making it a promising dielectric-magnetic component for microwave absorption applications [155]. Cai and colleagues reported a hydrothermal-freeze drying method to prepare MXene/GO/Co₃O₄ (MGC) aerogels. In this composite, MXene and GO nanosheets formed a continuous, honeycomb-like 3D framework through hydrogen bonding, with both nanosheet types exhibiting similar corrugated morphologies (Fig. 12c) [156]. Research indicates that the morphology and content of Co₃O₄ play a decisive role in the structural integrity of this framework. Due to their high zeta potential, Co₃O₄ nanofibers tend to induce severe aggregation of MXene and GO sheets, thereby disrupting the continuous honeycomb architecture. In contrast, a moderate loading of anisotropic Co₃O₄ nanorods helps maintain a continuously interconnected 3D structure, while excess loading also leads to structural

collapse and fails to form the desired porous architecture. Therefore, the introduction of an optimal amount of anisotropic Co_3O_4 nanorods synergistically optimizes the magnetic loss and dielectric loss capabilities. The MGCR₃ aerogel achieved a ultralow $RL_{\min}$ of -71.87 dB, with an EAB of 6.88 GHz at a matching thickness of 2.07 mm. Separately, Deng and colleagues developed a hydrothermal synthesis strategy that uses high-concentration strong alkali to protect MXene, and successfully preparing stable $\text{Ti}_3\text{C}_2\text{T}_x/\text{Co}_3\text{O}_4$ composites [157]. It is worth noting that without the protection of NaOH, pristine $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets are readily oxidizes from their edges in aqueous solution, and completely transforming to anatase titanium dioxide under high-temperature and high-pressure conditions. However, for samples prepared with high-concentration NaOH (≥ 2.5 M), the characteristic (002) diffraction peak of $\text{Ti}_3\text{C}_2\text{T}_x$ was well preserved in the XRD pattern, and almost no anatase TiO_2 impurity phase was detected. Based on these results, Deng's team proposed a proposed a credible oxidation protection mechanism (Fig. 12d): First, NaOH treatment promotes a reduction of F-terminal groups and an increase in O-/OH-terminal groups on the $\text{Ti}_3\text{C}_2\text{T}_x$ surface. The newly formed OH-terminal groups can be stably adsorbed at the vacant Ti sites on both sides of the $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets, preventing water molecules from directly contacting Ti atoms. Second, numerous OH^- ions and water molecules expand the interlayer spacing of $\text{Ti}_3\text{C}_2\text{T}_x$, which facilitates the reversible intercalation and adsorption of Na^+ ions, further increasing the steric hindrance between water molecules and active Ti atoms. Subsequently, these terminal groups also prevent O_2 molecules from oxidizing Ti atoms during the post-annealing process, with the terminal OH groups being gradually oxidized to more stable O-terminal groups. The protective agent must satisfy two conditions: extremely high solubility in water and a cation diameter smaller than the expanded interlayer spacing of MXene. Furthermore, concentrated solutions of salts with small ionic radii, complete ionization, and excellent water solubility (e.g., LiCl) are also expected to protect the $\text{Ti}_3\text{C}_2\text{T}_x$ structure. Guided by this protection mechanism, MXene/ Co_3O_4 composites' microwave absorption behavior can be tuned to achieve single-band, multi-band, or even broadband absorption via tuning the component ratio and sample thickness. At a

matching thickness of only 2.0 mm, this composite realizes electromagnetic absorption of over 90% across the entire 10.8–17 GHz frequency band.

Spinel-type mixed metal oxides of zinc cobaltate (ZnCo_2O_4) and nickel cobaltate (NiCo_2O_4), have emerged as promising microwave absorption components, benefiting from their intrinsically high electrical conductivity, strong polarization capability, and low raw material cost. Zeng's team (Fig. 12e) exploited the high specific surface area of MXene nanosheets as a conductive substrate, and achieve in-situ vertical growth of NiCo-LDH nanosheets both on the MXene surface and within its interlayers spacing [158]. This rational structural design effectively alleviates the severe agglomeration of NiCo-based oxides that typically occurs during high-temperature calcination, and largely preserves the integrity of the overall heterostructure. After calcination, the smooth surface of the precursor is converted into a rough morphology with abundant microporous structures. This evolved surface morphology and hierarchical porous architecture provide favorable conditions for multiple electromagnetic scattering and attenuation, further optimizing the microwave absorption efficiency. Consequently, this NiCo_2O_4 nanosphere-MXene heterostructure achieved excellent performance, with a $RL_{\min}$ of -72.3 dB, and the corresponding EAB covered 3.6 GHz when the sample thickness is 1.7 mm. Separately, Bao et al. reported an electrostatic self-assembly method to fabricated a $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ $\text{ZnCo}_2\text{O}_4@\text{ZnO}$ (MZCZ) composite (Fig. 12f) with abundant Schottky heterointerfaces [159]. By precisely tuning the MXene content, they achieved self-regulation of the built-in electric field (BIEF) strength and distribution, thereby improve the absorption capabilities of the composite. In this system, the $\text{ZnCo}_2\text{O}_4@\text{ZnO}$ (ZCZ) component forms a porous nanoflower-sphere architecture, which is self-assembled from ultrathin flexible nanosheets with smooth surface and numerous internal pores. When a moderate amount of MXene is introduced, the ZCZ nanoflowers are uniformly anchored onto the MXene surface, creating numerous Schottky heterointerfaces that are conducive to BIEF construction. However, excessive MXene coverage will compress and disrupt the ZCZ nanoflowers, causing damage to the surface structure and reducing the density of heterointerfaces, which consequently weakens the BIEF strength. The

constructed BIEF modulates the electronic transport characteristics, electron density distribution and band structure of the composite, and effectively promotes polarization relaxation. Electronic force analysis further confirmed the existence and dynamic responsiveness of the interfacial BIEF (Fig. 12 g). Due to the higher Fermi level of ZCZ, when an external electric field is applied opposing the BIEF direction, electrons accumulate on the MXene side to promote charge separation, and the counteracting force generated by BIEF drives the system toward dynamic equilibrium. Conversely, when the electric field aligns with the BIEF, accelerated electron migration occurs from the MXene side to the ZCZ side. At the Schottky barrier, a stable driving force is established due to the upward band bending of ZCZ, maintaining a relatively stable steady state. When the frequency of the incident electromagnetic wave matches the oscillation period of the spatial charges, the effective interfacial polarization induced by BIEF significantly attenuates the microwave energy. Guided by this BIEF optimization strategy, the MZCZ composite achieved a $RL_{\min}$ of -74.41 dB at 2.094 mm thickness, even at a thinner 1.501mm, the $RL_{\min}$ still maintained a high level of -69.78 dB.

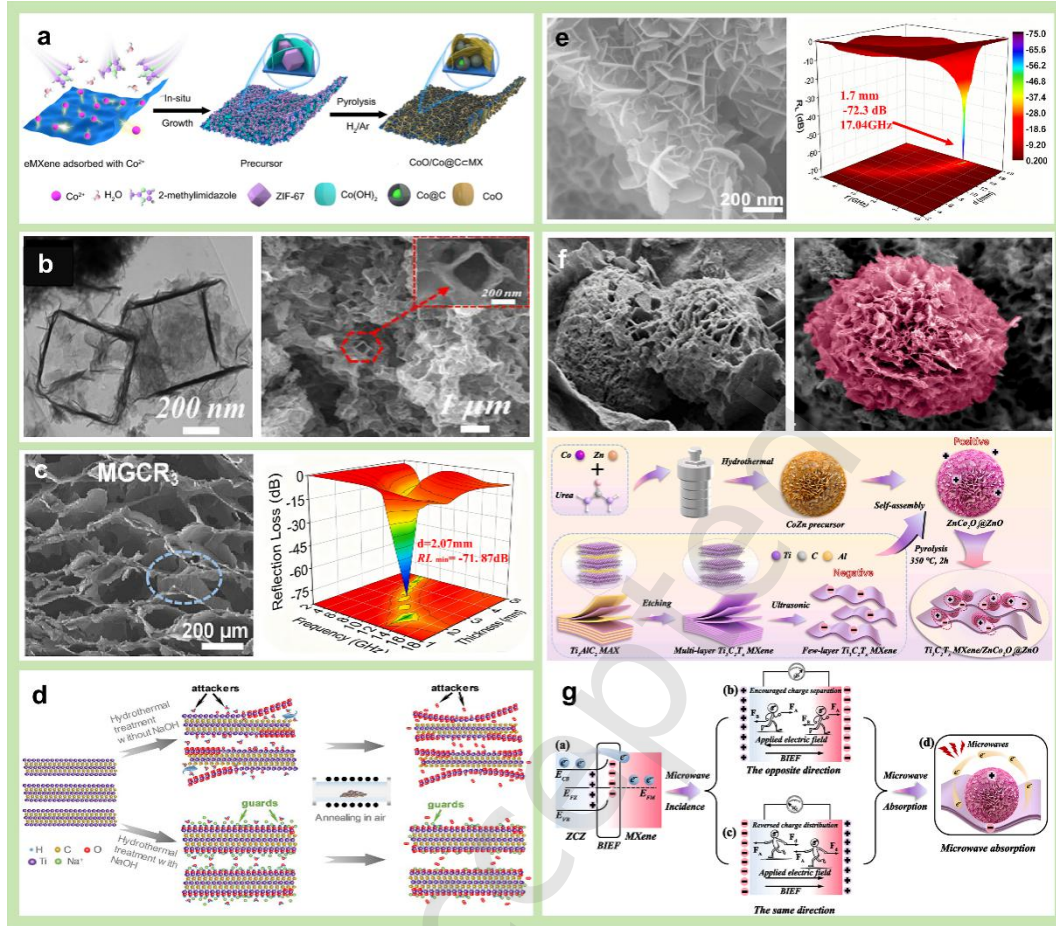


Figure 12 (a) Schematic diagram of the preparation process of CoO/Co@C/MX composites. Reproduced with permission from Ref. [153], © American Chemical Society 2022. (b) TEM/SEM images of MXene@TMOs. Reproduced with permission from Ref. [154], © Elsevier Ltd. 2024. (c) SEM images and 3D RL curves of MGCR₃. Reproduced with permission from Ref. [156], © Elsevier B.V. 2023. (d) Schematic diagram of the preparation process with or without sodium hydroxide. Reproduced with permission from Ref. [157], © Elsevier B.V. 2019. (e) SEM images and 3D RL curves of NiCo₂O₄ NSs-MXene composites. Reproduced with permission from Ref. [158], © Elsevier Ltd. 2022. (f) Preparation flow chart and SEM images of MXene/ZnCo₂O₄@ZnO sample. (g) Schematic diagram of electronic force analysis. Reproduced with permission from Ref. [159], © Elsevier B.V. 2024.

Integration of magnetic oxides with MXenes represents another effective optimization strategy for microwave absorption. The fundamental theoretical basis of this approach lies in utilizing the intrinsically high resistivity of oxides to effectively suppress high-frequency eddy current losses. This strategy is designed to compensate for the inherent limitations of pure MXenes in high-frequency microwave absorption, enabling strong microwave attenuation in higher frequency bands, and thus complementing the frequency applicability of pure metal-modified MXene systems.

Furthermore, the exposed metal cations and surface oxygen atoms of magnetic oxides can form strong coordination bonds with the terminal -OH and -F functional groups on MXene nanosheets. This interaction achieves stable anchoring of nano-sized oxides on the MXene matrix and effectively inhibits the agglomeration of oxide nanoparticles. Additionally, compared with most transition metal alloys, magnetic oxides simultaneously offer excellent chemical stability, lower material density, and reduced preparation cost, making them more suitable for large-scale production and practical applications. Certain spinel ferrites, represented by CoFe_2O_4 , also possess high magnetocrystalline anisotropy, which contributes to maintaining excellent high-frequency absorption stability. The flexible adjustability of A- and B-site ion combinations in the spinel crystal structure provides extensive design space for the synergistic tuning of electromagnetic parameters of MXene-based composites.

3.4 Magnetic metal sulfide-enhanced MXene MAMs

While magnetic oxides constitute a classic class of magnetic materials for microwave absorption, they often possess intrinsic limitations, such as wide band gaps and modest optoelectronic activity. Sharing an identical valence electron configuration with oxygen, sulfur gives rise to pronounced homology between magnetic sulfides and their oxide counterparts in both crystal structure and the intrinsic origin of magnetism. Conversely, the lower electronegativity and larger ionic radius of sulfur impart narrower band gaps, attenuated magnetic exchange interactions, and more tunable electronic properties to sulfides, establishing them as a promising candidate for MAMs. In contrast to conventional metal oxides, metal sulfides generally exhibit superior dielectric loss capabilities, favorable charge carrier mobility, inherently low density, and enhanced interfacial polarization. These combined attributes provide unparalleled advantages for the rational design of lightweight, high-performance MAMs [160-162].

Cobalt sulfide (CoS) possesses a stable hexagonal nickel-arsenide-type crystal structure, which consists of alternating close-packed sulfur layers and cobalt atoms that occupy the octahedral interstitial sites. This material exhibits weak magnetism at

room temperature, which originating from uncompensated surface spins or defect-induced effects at the nanoscale. This weak magnetism provides a physical basis for magnetic loss [163]. Liu's group prepared layered $\text{Ti}_3\text{C}_2\text{T}_x$ MXene via HF etching, and subsequently constructed a heterointerface-rich MXene/CoS composite microwave absorber [164]. In their work, hollow CoS microspheres with surface modification were assemble on MXene surface through layer-by-layer electrostatic self-assembly. By systematically optimizing the mass ratio between $\text{Ti}_3\text{C}_2\text{T}_x$ and CoS, the obtained material achieved a remarkable $RL_{\min}$ of -60.28 dB at 12.24 GHz at an ultra-thin matching thickness of only 1.81 mm, and achieved an EAB as wide as 3.04 GHz.

Beyond CoS, other members of the cobalt sulfide family, such as cobalt disulfide (CoS_2) and the cobalt-rich phase Co_9S_8 , have also been widely investigated as absorbing components for MXene-based electromagnetic wave absorption composites due to their tunable electronic structures and magnetic properties. As illustrated in Fig. 13a, Huo's team proposed a strategy based on "multidimensional heterostructure construction" and "magnetic-dielectric synergy" to prepare $\text{CoS}_2/\text{C}/\text{MXene}$ ternary composite carbon nanofibers [165]. In their synthetic route, polyacrylonitrile (PAN) precursors loaded with MXene nanosheets were first fabricated via electrospinning. During the subsequent carbonization step, the PAN nanofibers into a carbon matrix while reducing Co^{3+} to metallic cobalt nanoparticles. These nanoparticles were then sulfurized in situ using H_2S gas generated from thiourea, transforming them into CoS_2 particles with an average size of approximately 70 nm. The final architecture featured 0D CoS_2 nanoparticles uniformly anchored on 1D carbon nanofibers, which were themselves attached to 2D MXene nanosheets, forming an integrated "0D/1D/2D" multidimensional network (Fig. 13b). This design effectively suppressed the agglomeration of magnetic nanoparticles, and the carbon fiber coating mitigated the oxidative degradation of MXene. The 0D CoS_2 nanoparticles contributed high magnetocrystalline anisotropy, and sulfur vacancy-induced dipole polarization further enhanced dielectric loss, with their magnetic loss performance in the C-band surpassing that of some traditional alloys. The 2D MXene nanosheets not only acted

as a major source of interfacial polarization for the entire system, but also provided backbone for electron transport. Meanwhile, the 1D carbon nanofibers functioned as an additional dielectric loss medium to dissipate electromagnetic energy, while maintaining the structural stability of the composite. Leveraging this multidimensional synergy, the CoS₂/C/MXene composite delivered outstanding microwave absorption performance (Fig. 13c), with a low filler loading of 3 wt.% and an optimal thickness of only 2.5 mm, it achieving a $RL_{\min}$ as strong as -70.86 dB, and the EAB covered 90% of the X-ban.

In contrast to CoS₂, the cobalt-rich stable phase Co₉S₈ crystallizes in a cubic crystal structure. Its superior electronic conductivity, excellent chemical stability, and favorable band structure offer broader opportunities for interfacial engineering in cobalt sulfide/MXene composites [166]. Hou's team (Fig.13d) synthesized a multilayered Co₉S₈/C/Ti₃C₂T_x hybrid material with a distinctive cord-like morphology [167]. XPS analysis revealed partial oxidation of Ti₃C₂T_x after hydrothermal annealing, as indicated by pronounced changes in the Ti 2p orbital peaks. More importantly, the appearance of an S–C bond signal in the C 1s spectrum directly confirmed covalent interfacial bonding between Co₉S₈ and MXene. This strong chemical coupling, which surpasses conventional physical contact, facilitates interfacial charge accumulation and relaxation under alternating electromagnetic fields, thereby significantly enhancing interfacial polarization. Concurrently, the coexistence of Co²⁺ and Co³⁺ in the Co 2p spectrum indicates mixed valence states, and the incompletely filled d-orbitals impart metal-like conductivity and rapid charge-transfer capability, contributing to conductive loss. Electromagnetic parameter analysis confirmed that both the real and imaginary parts of the complex permittivity of the Co₉S₈/C/Ti₃C₂T_x-100 sample were markedly increased compared to pristine Ti₃C₂T_x, reflecting its enhanced dual capability for electromagnetic energy storage and dissipation. Consequently, with a Ti₃C₂T_x loading of 100 mg, the composite achieved a $RL_{\min}$ of -50.07 dB at a frequency of 7.6 GHz with a matching thickness of 2.51 mm, along with an EAB of 4.24 GHz.

Nickel sulfide (NiS), with its rich crystalline polymorphs and tunable electronic

transport properties, offers another crucial degree of freedom for regulating TMD/MXene composite systems. The semiconducting nature of NiS enables its electrical conductivity to be modulated enables, which is a highly attractive property for electromagnetic wave absorption. Specifically, semiconducting NiS and MoS₂ can promote charge trapping and accumulation at heterointerfaces and defect sites, which synergistically enhancing polarization relaxation under alternating electromagnetic fields [168]. Building on this concept, Chang et al. fabricated NiS/MoS₂/Ti₃C₂T_x multilayered hybrid absorbers [169]. During synthesis, Mo⁶⁺ was reduced to Mo⁴⁺ via a redox reaction with S²⁻ to form MoS₂ nanosheets, while metallic Ni spheres were in situ converted into NiS nanoparticles. Subsequently, these nanoparticles were encapsulated by the MoS₂ nanosheets and anchored onto the Ti₃C₂T_x layers, forming a hierarchical core-shell heterostructure. In this ternary system, semiconducting NiS and MoS₂ work synergistically contribute to dielectric loss, where NiS additionally provides the magnetic loss component. The Ti₃C₂T_x component serves as a conductive network and a platform for interfacial polarization. The synergistic interaction among these three constituents optimizes the overall electromagnetic attenuation capability and impedance matching characteristic. As a result, the composite delivered a $RL_{\min}$ of -58.49 dB at 2.4 mm, and the EAB_{max} reached 5.04 GHz at the matching thickness of 2.1 mm.

Ferrous sulfide (FeS) has also garnered extensive research interest for electromagnetic wave absorbing applications. As illustrated in Fig. 13e, Li's team successfully constructed lightweight magnetic composite foams (designated as GN/MXene/FeS) using GO and MXene as precursors [170]. In their synthesis, 3D hierarchical porous graphene@MXene composite foam was first fabricated via hydrothermal assembly and subsequent freeze-drying, and flower-like ferrous sulfide clusters were in situ grown on the surface of the porous framework. The as-fabricated foam exhibited a $RL_{\min}$ of -47.17 dB at a matching thickness of 4.78 mm, with a corresponding EAB of 6.15 GHz. By adjusting the MXene loading and applying a low-temperature heat treatment, the absorption capacity and bandwidth were further optimized. The optimized sample (GMF-300) delivered an improved $RL_{\min}$ of -50.68

dB, and the $EAB_{\max}$ was extended to 11.20 GHz, covering from 6.10 to 17.30 GHz, making it one of the best-performing MXene-based absorbers reported to date. The enhanced absorption performance is attributed to multiple synergistic mechanisms (Fig. 13f). Firstly, the rational hierarchical structure of the composite foam optimizes impedance matching, facilitating more electromagnetic wave entry into the absorber. Secondly, abundant internal voids prolong the propagation path of the incident waves via multiple reflections and scattering. Moreover, the rich heterogeneous interfaces among graphene, MXene, and flower-like FeS clusters induce strong interfacial polarization loss. Concurrently, the incorporation of the magnetic FeS phase introduces magnetic loss and eddy current loss. Furthermore, the unique flower-like morphology of FeS can introduce magnetic anisotropy, thereby optimizing the magnetic response of the composite. Notably, dielectric loss predominates in the low- and medium-frequency bands, while magnetic loss becomes dominant at higher frequencies. This complementary loss mechanism enables synergistic energy dissipation across a broad frequency range.

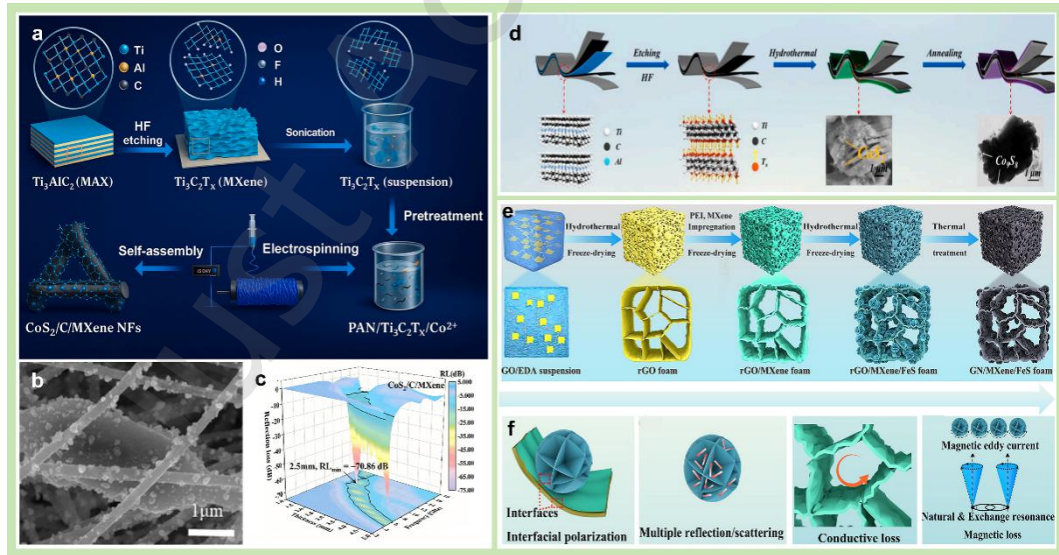


Figure 13 (a) Schematic diagram of the preparation process of $\text{CoS}_2/\text{C}/\text{MXene}$ composite nanofibers. (b) SEM images of $\text{CoS}_2/\text{C}/\text{MXene}$ samples. (c) 3D RL curve of $\text{CoS}_2/\text{C}/\text{MXene}$. Reproduced with permission from Ref. [165], © Elsevier Ltd. 2025. (d) Schematic diagram of the preparation process of composite samples. Reproduced with permission from Ref. [167], © Elsevier B.V. 2021. (e) Schematic diagram of the preparation process of $\text{GN}/\text{MXene}/\text{FeS}$ foam. (f) Microwave absorption mechanism of $\text{rGO}/\text{MXene}/\text{FeS}$ foam. Reproduced with permission from Ref. [170], © Elsevier Ltd. 2022.

Transitioning from monometallic to bimetallic sulfides enables further modulation of electronic structures and electromagnetic parameters via the synergistic effects of two distinct metal cations. Spinel-structured bimetallic sulfides such as NiCo_2S_4 and CuCo_2S_4 , exhibit high electronic conductivity and narrower bandgaps. This is attributed to the lower electronegativity of sulfur, which enhances the covalency of metal–sulfur bonds and increases electron cloud overlap. This compositional tunability offers an effective pathway for the continuous optimization of electromagnetic properties [171]. As shown in Fig. 14a, Pan and colleagues constructed a hierarchical, nest-like low-dimensional aggregate (denoted as MX@Mo@NCS) assembled from 2D MXene, 1D MnO_2 nanorods, and 0D NiCo_2S_4 nanoparticles [172]. In the fabrication, amorphous MnO_2 first underwent Ostwald ripening to form $\alpha\text{-MnO}_2$ nanorods. Subsequently, sulfide ions from decomposed thioacetamide react with Ni^{2+} and Co^{2+} ions to generate NiCo_2S_4 nanoparticles. Finally, these components self-assemble into the low-dimensional aggregate via electrostatic attraction and hydrogen bonding. Microscopic characterization (Fig. 14b) reveals that high-density MnO_2 nanorods are densely distributed within MXene interlayers, interweaving to form a nest-like hierarchical network, which enhances multiple internal reflections and scattering of incident electromagnetic waves. The NiCo_2S_4 nanoparticles are tightly clustered on the MnO_2 nanorod surfaces and uniformly dispersed between MXene layers. Their relatively lower electrical conductivity establishes an impedance transition barrier on the highly conductive MXene surface, mitigating direct microwave–MXene interaction and thereby optimizing impedance matching. Electromagnetic parameter analysis further indicates that pristine MXene suffers from severe impedance mismatch due to its excessively high and singular dielectric loss. The introduction of MnO_2 nanorods shifts the normalized input impedance closer to unity over a broad frequency range, achieving effective broadband impedance matching. The additional incorporation of the magnetic-loss component NiCo_2S_4 further refines the impedance matching performance within the 3.5–18.0 GHz range. Therefore, the sample can achieve an EAB of 5.8 GHz at a thickness of 2.0 mm. When the matching thickness is optimized

to 2.17 mm, it delivers a $RL_{\min}$ of -59.2 dB, thus simultaneously realizing strong absorption, wide bandwidth, and an ultrathin profile.

Additionally, Fang et al. constructed MXene@CuCo₂S₄ heterostructures via an electrostatic self-assembly strategy, with the fabrication schematic illustrated in Fig. 14c [173]. Laminar Ti₃C₂T_x MXene was first successfully prepared via the selective etching of Al atomic layers from the parent Ti₃AlC₂ phase. Flower-like CuCo₂S₄ microspheres were then synthesized via a hydrothermal method. The strong affinity of Cu²⁺ and Co²⁺ cations for S²⁻ anions drove rapid nucleation of CuCo₂S₄, and the high surface energy of the nuclei guided the oriented 2D growth of nanosheets. Ethylene glycol and CTAB acted synergistically to inhibit agglomeration and promote the uniform assembly of hierarchical flower-like structures. The microsphere morphology could be precisely controlled via changing the molar ratio of Cu/Co precursor, with higher Co concentrations favoring more complex flower-like architectures. Notably, CTAB also rendered the CuCo₂S₄ microsphere surface positively charged, providing the driving force for electrostatic self-assembly with negatively charged Ti₃C₂T_x MXene nanosheets. The introduction of cobalt endowed the MXene@CuCo₂S₄ composite with a M_s of 0.10 emu·g⁻¹. Although relatively modest, this magnetization provided effective magnetic loss compensation in the GHz range. Under optimized conditions, the MXene@CuCo₂S₄-8 composite delivered a $RL_{\min}$ of -60.02 dB at 14.88 GHz, when the matching thickness was set as 1.61 mm. Furthermore, at a slightly adjusted thickness of 1.65 mm, it exhibited an EAB as wide as 6.02 GHz, which completely covered the Ku-band. It was also found that tunable effective absorption covering the C-band, X-band and Ku-band could be realized by finely modulating the thickness of the absorber.

Building on bimetallic sulfides precursors, introducing a third metal element further expands the electronic structure tunability of sulfide systems. For instance, NiCoMo-S inherits the spinel-type crystal framework of NiCo₂S₄ but incorporates molybdenum in a high oxidation state. The d-orbitals of Mo reconfigure the band structure, enriching edge-active sites while simultaneously enhancing electrical conductivity and structural stability. This “third-metal doping” strategy represents a

key evolution from binary to multicomponent sulfides systems, introducing an additional dimension for synergistically optimizing impedance matching and dielectric loss [174]. Yang's team fabricated flower-like NiCoMo-S absorbers via a hydrothermal method, followed by electrostatic self-assembly with MXene to construct a NiCoMo-S/MXene (NCMM) composite that features abundant heterogeneous interfaces (Fig. 14d) [175]. The NiCoMo-S is tightly anchored onto the MXene surface, forming intimate interfacial contact and numerous heterogeneous interfaces that effectively enhance interfacial polarization loss. Electromagnetic parameter measurements revealed that the sulfidation degree significantly influences the complex permittivity and, consequently, the microwave absorption performance of the NCMM composites. With increasing sulfidation, the real part of permittivity and the corresponding absorption performance first increase and then decrease, indicating that sulfidation degree is a critical governing parameter. Furthermore, filler loading exerts a strong influence: insufficient loading fails to establish an effective conductive network, leading to inadequate attenuation, whereas excessive loading causes severe impedance mismatch. By rationally integrating the complementary advantages of NiCoMo-S and MXene, the optimized NCMM hybrid with an appropriate sulfidation degree and 20 wt.% filler loading achieved a $RL_{\min}$ of -56.4 dB at 12.66 GHz (2.61 mm). When the absorber thickness was adjusted to 2.69 mm, the composite demonstrated an EAB as wide as 8.1 GHz (9.9–18.0 GHz), which covers nearly the entire X-band and the full Ku-band.

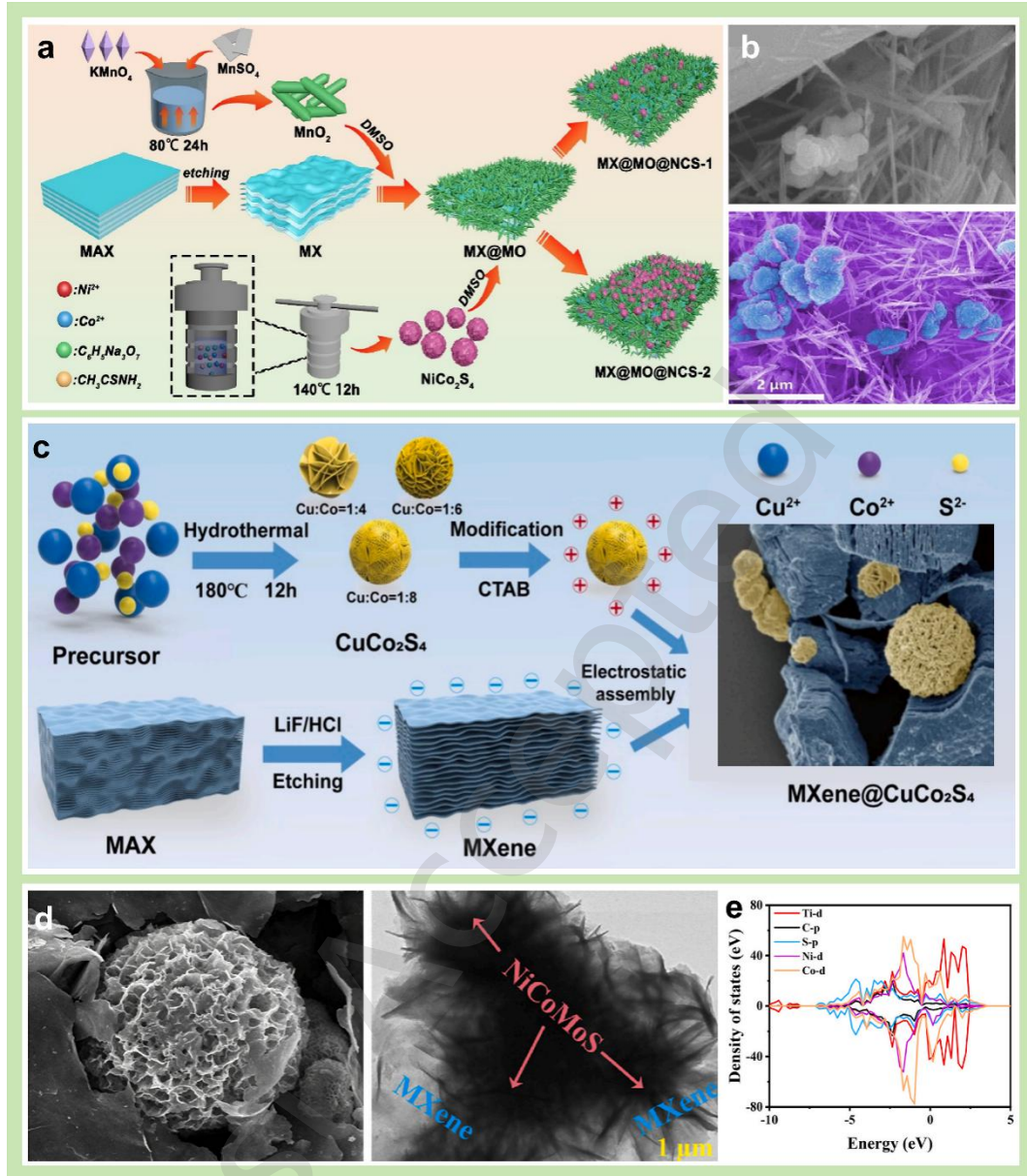


Figure 14 (a) Preparation route of MX@Mo@NCS. (b) SEM images of MX@MO@NCS. Reproduced with permission from Ref. [172], © Elsevier B.V. 2022. (c) Schematic diagram of the preparation process of MXene@CuCo₂S₄ heterostructures. Reproduced with permission from Ref. [173], © Elsevier B.V. 2025. (d) SEM/TEM images of NCMM. (e) Density of states curve of NiCoMoS/MXene heterojunction. Reproduced with permission from Ref. [175], © Elsevier Ltd. 2025.

Based on the studies discussed, embedding magnetic metal sulfides as the magnetic functional phase into MXene-based electromagnetic wave absorbing systems primarily introduces magnetic losses dominated by exchange resonance and natural resonance. Eddy current loss is effectively suppressed due to the moderate conductivity of sulfides. The semiconductor properties of these sulfides allow for

reduction of the excessively high conductivity of pristine MXene, while still retaining a certain level of electrical conductivity, thereby optimizing impedance matching and balancing low-frequency magnetic loss with high-frequency absorption stability. This unique conductivity tuning range, which lies between metals and oxides, represents a distinct advantage of sulfide systems. Furthermore, sulfur atoms can form strong covalent bonds and coordination interactions with the -OH and -F functional groups on the surface of MXene nanosheets. This ensures the stable anchoring of the magnetic functional phase within the MXene interlayers and provides abundant charge transfer channels for enhanced interfacial polarization. From an engineering application perspective, sulfide systems offer superior oxidation and corrosion resistance compared to magnetic metals. Their relatively low raw material costs and straightforward preparation processes make them suitable to meet the requirements of lightweight and large-scale production. Additionally, the rich metal valency states and tunable semiconductor characteristics of sulfides enable flexible combinations of multiple metal components. This provides significant degrees of freedom for the synergistic optimization of complex permittivity and complex permeability, which in turn improves the electromagnetic wave absorption performance of the composite.

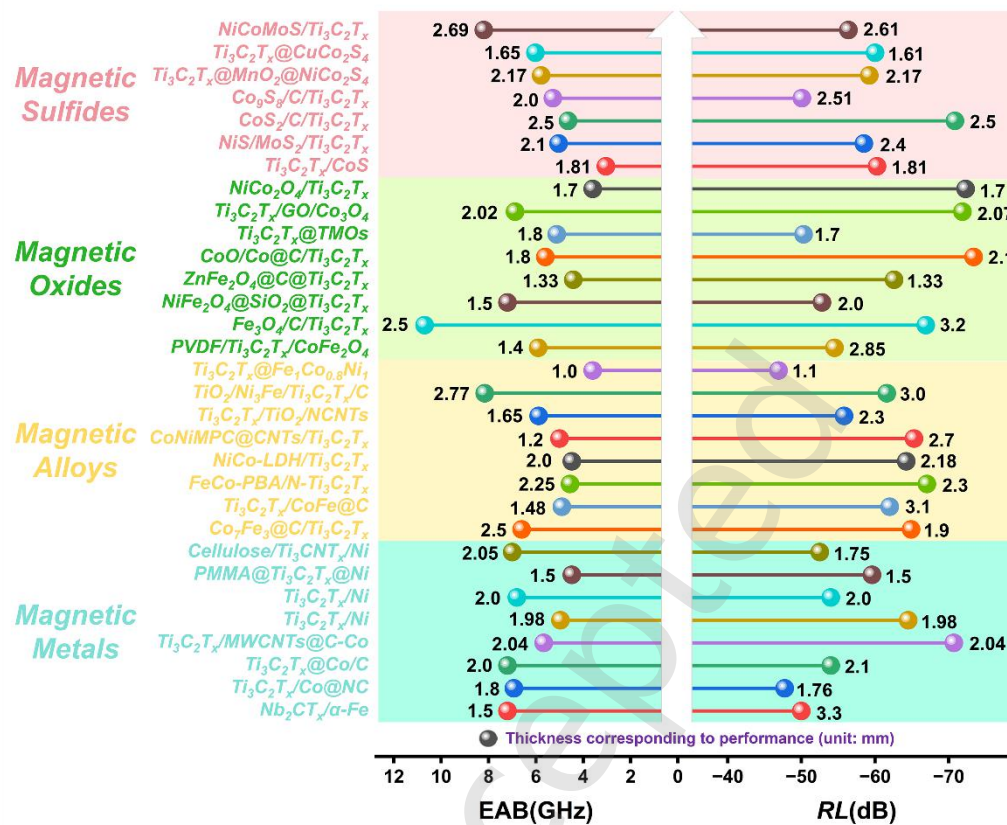


Figure 15 Microwave absorption performance comparison of typical magnetic/MXene composites

4 Challenges and prospects

To sum up, magnetic nanomaterial-reinforced MXene MAMs have significantly improved in critical performance parameters, such as lightweight construction, extensive bandwidth, and robust absorption. This progress is primarily due to the synergistic coupling of dielectric and magnetic losses, augmented heterointerface polarization, and meticulous microstructural optimization, establishing it as a cutting-edge area of research in electromagnetic protection and stealth technology. In other words, the regulation of interaction between MXenes and magnetic components is an effective strategy for constructing high-performance MAMs. This review systematically delineates construction strategies involving four distinct categories of magnetic functional phases with MXenes: magnetic metals, magnetic alloys, magnetic metal oxides, and magnetic metal sulfides. The key microwave absorption parameters of typical magnetic nanomaterial-reinforced MXene composites are systematically

summarized in Fig. 15, including EAB, matching thickness, and $RL_{\min}$. The integration of magnetic elements within MXenes can yield superior microwave absorption capabilities. It is worth noting that the synthesis methods play an important role in governing the interactions between MXenes and magnetic components, such as interfacial bonding configuration, charge transfer kinetics, and polarization relaxation. The tunable interfacial interaction strength, ranging from chemical covalent linkage to weak physical adsorption, intrinsically manipulates electromagnetic loss behavior and impedance matching, thereby constructing a definitive structure–performance paradigm for high-efficiency MAMs.

Although the aforementioned composites exhibit distinct advantages in microwave absorption, some challenges remain in moving from laboratory-scale performance validation to practical engineering applications. Firstly, the precision in microstructural control remains insufficient. MXene nanosheets inherently possess a layered topological structure, making them highly prone to restacking driven by interlayer van der Waals forces. Concurrently, all four types of magnetic nanomaterials tend to agglomerate significantly due to their high surface energy. The combination of these phenomena leads to the interfacial contact area of the composite material being far lower than the theoretical optimum, making it difficult to uniformly construct an efficient 3D conductive-magnetic coupling network. A more fundamental issue is that most current structural design strategies focus primarily on simple binary planar composite structures, and lack precise construction and systematic regulation of multi-dimensional heterointerfaces. This limitation prevents the full exploitation of the synergistic potential of interfacial polarization, conduction loss and magnetic loss. Secondly, an inherent imbalance exists between electromagnetic parameter matching and loss synergy. The incorporation of magnetic components can enhance impedance matching by the augmentation of magnetic permeability; nevertheless, exact control over the type, content, size, and spatial distribution of magnetic nanomaterials during the practical synthesis process remains challenging. At the same time, excessively strong dielectric loss will cause most incident electromagnetic waves to be reflected at the material surface. Conversely, insufficient magnetic loss results in limited

attenuation capability for the waves that have entered the material interior. This inherent imbalance fundamentally limits the simultaneous achievement of broad bandwidth, strong absorption and thin thickness, which are the core performance metrics for high-performance microwave absorbers. Thirdly, poor environmental stability and service reliability represent another critical challenge. MXenes have abundant oxygen-containing functional groups on their surfaces, making them highly susceptible to irreversible oxidation in humid and high-temperature environments. This oxidation will cause the drift of the material's electromagnetic parameters and the degradation of microwave absorption performance. Magnetic nanomaterials also face intrinsic stability challenges: pure metals and metal alloys are prone to corrosion or oxidation in hot and humid environments, while metal sulfides are at risk of desulfurization and oxidative phase transition at elevated temperatures, both leading to rapid decay of electromagnetic performance. Most reported studies only characterize short-term electromagnetic performance under ambient static conditions, and there is a severe lack of systematic evaluation on the practical service properties required for real-world applications, such as flexibility, compressive strength, extreme temperature cycle resistance and corrosion resistance. This research gap severely restricts the practical application of MXene-based MAMs in harsh application scenarios such as aerospace and military stealth. Furthermore, currently reported fabrication strategies, including in-situ growth, solvothermal synthesis, freeze-drying, electrostatic self-assembly and MOF precursor pyrolysis, are mainly limited to laboratory-scale operations. These processes are generally complex, time-consuming, and difficult to scale up for industrial mass production. Although milder etching systems based on HCl/LiF have been developed for MXene preparation, their production yield and large-area uniformity still require substantial improvement. In addition, the commonly used magnetic precursors, such as MOFs and noble metal salts are high in cost, which further hinders the commercialization and large-scale application of these high-performance MAMs.

Integrating magnetic functional phases into MXene matrices is acknowledged as a fundamental approach to enhancing the microwave absorption capabilities of

MXene-based composites. This is not merely a competition of dominance among various materials but a distinction of functional niches within the design space of MXene-based MAMs, which collectively provide a complementary functional system for high-performance microwave absorption. Future breakthroughs in magnetic nanomaterial-reinforced MXene MAMs are expected to focus on multi-dimensional heterostructure design. This strategy requires the integration of DFT (density functional theory) modeling and machine learning methodologies to distinctly reveal the interfacial synergistic characteristics of MXenes and magnetic components, consequently supporting the rational construction of multi-component composite frameworks. Concurrently, machine learning methodologies are advantageous for predicting and investigating more viable MXene-based MAMs reinforced by magnetic nanomaterials. Moreover, the development of continuous manufacturing techniques, such as electrostatic self-assembly, solid reaction process, and spray drying, must be advanced to improve production efficiency and batch-to-batch consistency. Based on this foundation, the integration of multifunctional properties (e.g., thermal management, infrared stealth, and flexible wearable features in synergy with absorption functions) should be pursued to develop environmentally stable “absorption-protection-adaptation” integrated materials, which will accelerate the industrial application of these materials in fields such as aerospace [177-179].

Although MXene/magnetic nanomaterial composites still face multiple challenges toward high-performance microwave absorption, including precise structural control, environmental stability, and large-scale production, systematic research focusing on multidimensional heterostructure design, theoretical modeling guidance, and continuous process innovation are steadily opening up their practical engineering application prospects. It is widely accepted that intelligent absorbing materials featuring the “lightweight, broad bandwidth, and strong absorption” properties will become the core development direction of next-generation electromagnetic protection technologies. This review attempts to provide a theoretical basis for the advancement of MXene-based MAMs by evaluating material design principles and performance enhancement techniques, while also offering a novel

framework for the creation of the next generation of integrated electromagnetic functional materials.

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Declaration of competing interest

The authors declare no conflict of interest.

Author contribution statement

Jiahong Ren: Writing-original draft. Heguang Liu: Conceptualization, Funding acquisition, writing-review & editing. Jieli Lyu: Funding acquisition. Na Tian, Caiyin You: Funding acquisition, Supervision. All the authors have approved the final manuscript.

References

- [1] Liu, A.; Zhang, Y. L.; Xu, X. S.; Kong, J.; Gu, J. W. Multi-Field Synergy for Orchestrating Filler Angles in Polyimide Aerogels with Switchable Electromagnetic Interference Shielding. *Adv. Mater.* **2026**, *38*, e73267.
- [2] Tian, Z. Z.; Jia, T. M.; Kan, X. C.; Zhan, B. B.; Ding, J. F.; Qu, Y. P.; Gong, X.; Chen, Y. L.; Qi, X. S. Polarization Loss Enhancement Induced by Interfacial Contact Regulation Strategy to Develop Nickel Silicate/Reduced Graphene Oxide for Microwave Absorption and Corrosion Resistance. *Rare Met.* **2026**, *45*, e70327.
- [3] Qi, J. M.; Liang, C. B.; Ruan, K. P.; Li, M. K.; Guo, H.; He, M. K.; Qiu, H.; Guo, Y. Q.; Gu, J. W. Cactus-like Architecture for Synergistic Microwave Absorption and Thermal Management.

- [4] Kaur, M.; Kakar, S.; Mandal, D. Electromagnetic interference. *IEEE* **2011**, *4*, 1-5.
- [5] Bai, T. T.; Guo, Y.; Liu, H.; Song, G.; Zhang, D. B.; Wang, Y. M.; Mi, L. W.; Guo, Z. H.; Liu, C. T.; Shen, C. Y. Achieving enhanced electromagnetic shielding and absorption capacity of cellulose-derived carbon aerogels via tuning the carbonization temperature. *J. Mater. Chem. C* **2020**, *8*, 5191-5201.
- [6] Hu, P. T.; Dong, S.; Li, X. T.; Chen, J. M.; Zhang, X. H.; Hu, P.; Zhang, S. S. A low-cost strategy to synthesize MnO nanorods anchored on 3D biomass-derived carbon with superior microwave absorption properties. *J. Mater. Chem. C* **2019**, *7*, 9219-9228.
- [7] Zhang, X.; Qiao, J.; Zhao, J. B.; Xu, D. M.; Wang, F. L.; Liu, C.; Jiang, Y. Y.; Wu, L. L.; Cui, P.; Lv, L. F.; Wang, Q.; Liu, W.; Wang, Z.; Liu, J. R. High-efficiency electromagnetic wave absorption of cobalt-decorated NH₂-UIO-66-derived porous ZrO₂/C. *ACS Appl. Mater. Interfaces* **2019**, *11*, 35959-35968.
- [8] Liu, A.; Xu, X. S.; Qiu, H.; Guo, H.; He, M. K.; Yu, Z.; Zhang, Y. L.; Gu, J. W. Bioinspired hollow heterostructure fillers for enhanced electromagnetic interference shielding in polyimide aerogels. *InfoMat* **2025**, *7*, e70060.
- [9] Wang, H. M.; Zhan, B. B.; Zhang, Y. R.; Tan, Z. Y.; Ding, J. F.; Chen, Y. L.; Qu, Y. P.; Qi, X. S. Multi-scale synergistic regulation strategy to develop mesoporous carbon hollow nanospheres/bean-shaped nanofibers for corrosion resistance, flexible and lightweight microwave absorbers. *Research* **2025**, *9*, 1051.
- [10] Tbahrity, H. F.; Benbernou, M.; Satani, A.; Rebezov, M.; Arcot, R.; Thiruvengadam, M.; Shariati, M. A. Impact of electromagnetic fields on circadian rhythms: molecular and physiological insights. *Sleep Biol. Rhythms* **2026**, *24*, 195-214.
- [11] Green, M.; Liu, Z.; Xiang, P.; Tan, X.; Huang, F.; Liu, L.; Chen, X. Ferric metal-organic framework for microwave absorption. *Mater. Today Chem.* **2018**, *9*, 140-148.
- [12] Hou, H. B.; Yang, Q.; Gao, Y.; Ou, Y.; Wang, Z.; Yi, S.; He, J. F.; Ma, L.; Meng, F. B. Progress in supercritical CO₂ foamed polymer composites for electromagnetic protection: from rational structural design to absorption-dominated performance. *Acta Phys.-Chim. Sin.* **2026**, 100300.
- [13] Ray, S.; Panwar, R. Advances in Polymer-Based Microwave Absorbers—From Design

- Principles to Technological Breakthroughs: A Review. *IEEE J. Fle. Electron.* **2024**, *3*, 401-417.
- [14] Liang, C. M.; Hou, Z. L.; Koo, M. C.; Xu, F. F.; Bai, S.; Bai, Y. X.; Zhang, Y.; Cai, B.; Zhao, P. Y.; Wang, G. S. Modulating electromagnetic response through the regulation of built-in electric fields. *J. Mater. Sci. Technol.* **2026**, *248*, 126-134.
- [15] Zhang, Y. L.; Gu, J. W. Ultrathin and flexible electromagnetic interference shielding films by interface-confinement strategy. *Sci. China Mater.* **2025**, *69*, 2968–2969.
- [16] He, M. K.; Zhong, X.; Lu, X. H.; Hu, J. W.; Ruan, K. P.; Guo, H.; Zhang, Y. L.; Guo, Y. Q.; Gu, J. W. Excellent Low-Frequency Microwave Absorption and High Thermal Conductivity in Polydimethylsiloxane Composites Endowed by Hydrangea-Like CoNi@BN Heterostructure Fillers. *Adv. Mater.* **2024**, *36*, 2410186.
- [17] Ren, J. N.; Mu, Z. X.; Sellami, R.; El-Bahy, S. M.; Liang, G. M.; Guo, J.; Xie, P.; El-Bahy, Z. M.; Guo, Z.; Hou, H. Multifunctions of microwave-absorbing materials and their potential cross-disciplinary applications: a mini-review. *Adv. Compos. Hybrid Mater.* **2025**, *8*, 202.
- [18] Xu, W. B.; Yang, Y. R.; Wang, Y. Z.; Zhang, Y. L.; Li, T. H.; Liu, A.; Gong, W.; Gu, J. W. Polymer-Based Composite Fibers for Electromagnetic Interference Shielding. *SusMat* **2026**, *6*, e70071.
- [19] Li, K. Y.; Sun, H.; Zhang, X.; Zhang, S.; Dong, H. W.; Zhu, C. L.; Chen, Y. J. Micro-nanospheres assembled with helically coiled nitrogen-doped carbon nanotubes: fabrication and microwave absorption properties. *Mater. Design* **2020**, *186*, 108290.
- [20] Du, Y. C. Advances in carbon-based microwave absorbing materials. *Materials* **2022**, *15*, 1359.
- [21] Meng, X. F.; Xu, W. L.; Ren, X. J.; Zhu, M. Y. Progress and challenges of ferrite matrix microwave absorption materials. *Materials* **2024**, *17*, 2315.
- [22] Zhan, B. B.; Yiru Zhang, Y. R.; Tan, Z. Y.; Xie, A. M.; Gong, X.; Peng, Q.; Yang, J. L.; Qu, Y. P.; Qi, X. S. Multi-dimensional, multi-interfacial, and multi-path synergy enables broadband absorption, corrosion resistance, Joule heating, and thermal performances in hierarchical carbon/Ni nanoparticles-carbon nanocoils foams. *InfoMat* **2026**, *8*, e70098.
- [23] Chen, L.; Zhu, C. Y.; Si, Y.; Yang, Q. B.; Chen, X. Y.; Zhou, C. P. Enhanced electromagnetic wave absorption performance of multi-layer Fe₃O₄@rGO composite absorber. *Appl. Surf. Sci.*

2025, 688, 162434.

- [24] Song, Q.; Ye, F.; Kong, L.; Shen, Q. L.; Han, L. Y.; Feng, L.; Yu, G. J.; Pan, Y. A.; Li, H. J. Graphene and MXene nanomaterials: toward high - performance electromagnetic wave absorption in gigahertz band range. *Adv. Funct. Mater.* **2020**, 30, 2000475.
- [25] Zhou, Y. X.; Zhang, Y. L.; Ruan, K. P.; Guo, H.; He, M. K.; Qiu, H.; Gu, J. W. MXene-based fibers: Preparation, application, and prospects. *Sci. Bull.* **2024**, 69, 2776-2792.
- [26] Zhu, L. L.; Wu, W. W.; Chen, J. J.; Hu, Z. M.; Yu, J. R.; Wang, Y. High-performance electromagnetic wave absorption by two-dimensional mesoporous monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. *Chem. Eng. J.* **2024**, 488, 150649.
- [27] Chang, M.; Li, Q. Y.; Jia, Z. R.; Zhao, W. R.; Wu, G. L. Tuning microwave absorption properties of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-based materials: component optimization and structure modulation. *J. Mater. Sci. Technol.* **2023**, 148, 150-170.
- [28] Koo, M. C.; Zhang, Y.; Cai, B.; Liang, C. M.; Shi, S. H.; Peng, H. L.; Yang, S. H.; Sun, X. B.; Wang, G. S. Enhancing microwave absorbing properties of $\text{C}/\text{TiO}_2/\text{NiNW}$ composites through built-in electric field effect. *J. Mater. Sci. Technol.* **2026**, 244, 102-110.
- [29] Zhou, Y. X.; Zhang, Y. L.; Pang, Y. H.; Guo, H.; Guo, Y. Q.; Li, M. K.; Shi, X. T.; Gu, J. W. Thermally Conductive $\text{Ti}_3\text{C}_2\text{T}_x$ Fibers with Superior Electrical Conductivity. *Nano-Micro Lett.* **2025**, 17, 235
- [30] Xiao, J. X.; Zhan, B. B.; Tan, Z. Y.; Ding, J. F.; Qu, Y. P.; Gong, X.; Peng, Q.; Zhong, W.; Chen, Y. L.; Qi, X. S. Integration of photo-driven rapid self-healing and environmental robustness for durable electromagnetic wave absorbing elastomers. *InfoMat* **2026**, 8, e70127.
- [31] Wu, J. B.; Li, H. G. MXene-based flexible electronics: current advances and future perspectives. *Sci. China Mater.* **2025**, 68, 4360-4363.
- [32] Wang, Q.; Su, X. L.; Jia, Y.; Liu, Y.; Shahzad, F. Regulation of microstructure and absorption properties of MXene materials: theoretical and experimental. *Adv. Sci.* **2025**, 12, e09994.
- [33] Ma, Y. Z.; Wei, S. N.; Liu, R. X.; Sun, L. N.; Wang, W. A review on MXene-based microwave absorption composites: engineering, component optimization and structure regulation. *J. Mater. Chem. C* **2024**, 12, 9068-9093.
- [34] Deng, N. D.; Li, J.; Hong, Y.; Zhang, Z. Y.; Chen, Z. G.; Zhang, Z. Y.; Chen, Z. G.; Zhang, Z. Y.; Xu, T. T.; Li, Y.; Zhou, Z. X. The bimetallic MXene/ Fe_3O_4 composites with

- dielectric-magnetic synergy loss enable robust electromagnetic wave absorption. *Appl. Phys. Lett.* **2025**, *127*, 131903.
- [35] Xiang, Z.; Shi, Y. Y.; Zhu, X. J.; Cai, L.; Lu, W. Flexible and waterproof 2D/1D/0D construction of MXene-based nanocomposites for electromagnetic wave absorption, EMI shielding, and photothermal conversion. *Nano-Micro Lett.* **2021**, *13*, 150.
- [36] Cheng, H. R.; Pan, Y. M.; Wang, X.; Liu, C. T.; Shen, C. Y.; Schubert, D. W.; Guo, Z. H.; Liu, X. H. Ni flower/MXene-melamine foam derived 3D magnetic/conductive networks for ultra-efficient microwave absorption and infrared stealth. *Nano-Micro Lett.* **2022**, *14*, 63.
- [37] Wei, J. Y.; Liang, Q. Q.; Kan, X. C.; Tan, Z. Y.; Zhan, B. B.; Ding, J. F.; Qu, Y. P.; Peng, Q.; Yang, J. L.; Qi, X. S. Constructing Porous Magnetic Ni@C-Anchored Carbon Foams for Excellent Magnetic-Dielectric Synergy to Develop Integrated Microwave Absorbers with Efficient Thermal Insulation and Antibacterial Properties. *Sci. China Mater.* **2026**, *69*, 4994–5006.
- [38] Yu, C.; Peng, J. H.; Guo, J. H.; Yin, Z. H.; Lv, S. X.; Jiang, X. H. Facile Preparation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene@Zn-Mn Ferrite Composites with Enhanced Microwave Absorption Performance. *ACS Appl. Electron. Mater.* **2022**, *4*, 5582-5593.
- [39] Wang, Y.; Qu, Z. J.; Wang, W.; Qian, H. F.; Song, X. Y.; Yu, D. Multidimensional nanomaterials synergistic polyimide nanofiber/MXene/ NiFe_2O_4 hybrid aerogel for high-performance microwave absorption. *Chem. Eng. J.* **2023**, *470*, 144435.
- [40] Zhu, Y.; An, X. P.; Wang, J. N.; Zhu, C. C.; Nan, K.; Wang, Y. Tailored Schottky heterojunction and magnetoelectric synergy for optimizing MXene-based microwave absorbers. *Chem. Eng. J.* **2025**, *528*, 172355.
- [41] Hu, X. F.; Zhang, Y. L.; Guo, H.; He, M. K.; Qiu, H.; Shi, X. T.; Wang, L.; Gu, J. W. Multifunctional Flexible WPU Composite Aerogels with Sandwich Structure for Dual-Sided Low-Reflection Electromagnetic Interference Shielding. *Adv. Funct. Mater.* **2025**, *36*, e17665.
- [42] Xia, Q. X.; Miao, R. L.; Guo, W.; Xia, M.; Wang, L. B.; Hu, Q. K.; Zhou, A. G. Self-assembled Fe_3O_4 nanoparticles on V_2C MXene for enhanced supercapacitor and microwave absorption applications. *J. Adv. Ceram.* **2025**, *14*, 9221049.
- [43] Nezafat, Z.; Jafari, G.; Javanshir, S.; Peymanfar, R. MXene-based metal oxide/metal

composites for microwave absorption and shielding: recent advances and future perspectives.

Adv. Compos. Hybrid Mater. **2025**, *8*, 447.

- [44] Zhao, Z. H.; Shi, B.; Wang, T.; Wang, R. M.; Chang, Q.; Yun, J. J.; Zhang, L. M.; Wu, H. J. Microscopic and macroscopic structural strategies for enhancing microwave absorption in MXene-Based composites. *Carbon* **2023**, *215*, 118450.
- [45] Zhao, P. Y.; Peng, H. L.; Cai, B.; Zhou, L.; Liang, C. M.; Koo, M. C.; Wang, H. Y.; Wu, J. T.; Hou, Z. L.; Wang, G.-S. Mechanism decoupling of impedance matching and attenuation enhancement via spatial distribution of loading components. *Adv. Funct. Mater.* **2026**, *36*, e18479.
- [46] Rozanov, K. N.; Koledintseva, M. Y. Matching conditions for a homogeneous absorbing layer. *Procedia Eng.* **2017**, *216*, 79-84.
- [47] Yang, S. Y.; Wu, P.; Sheng, Y. F.; Dong, Y. W.; Li, Z. W.; Wang, T.; Qiao, L.; Li, F. S. On the Quality Criteria for Microwave Absorbing Materials. *Adv. Electron. Mater.* **2025**, *11*, e00239.
- [48] Hou, Z. L.; Gao, X. S.; Zhang, J. Y.; Wang, G. S. A perspective on impedance matching and resonance absorption mechanism for electromagnetic wave absorbing. *Carbon* **2024**, *222*, 118935.
- [49] Zhu, T. G.; Sun, Y.; Wang, Y. J.; Xing, H. N.; Zong, Y.; Ren, Z. Y.; Yu, H. P.; Zheng, X. L. Controllable synthesis of MOF-derived $\text{Fe}_x\text{Ni}_{1-x}\text{@C}$ composites with dielectric-magnetic synergy toward optimized impedance matching and outstanding microwave absorption. *J. Mater. Sci.* **2021**, *56*, 592-606.
- [50] Ren, S. N.; Yu, H. J.; Wang, L.; Huang, Z. K.; Lin, T. F.; Huang, Y. D.; Yang, J.; Hong, Y. H.; Liu, J. Y. State of the art and prospects in metal-organic framework-derived microwave absorption materials. *Nano-Micro Lett.* **2022**, *14*, 68.
- [51] Yang, Q.; Hou, H. B.; Lu, Y. X.; Guo, Z. Q.; Sun, J. X.; Zhang, P.; Yang, T.; Meng, F. B. Cascaded Broadband Low-Frequency Microwave Absorption Covering P- to C-Band in Ultra-Thin Metamaterials via Synergistic Local-Field and Loss-Field Enhancement. *Nano-Micro Lett.* **2026**, *18*, 407.
- [52] Zhang, Z. W.; Cai, Z. H.; Zhang, Y.; Peng, Y. L.; Wang, Z. Y.; Xia, L.; Ma, S. P.; Yin, Z. Z.; Wang, R. F.; Cao, Y. S.; Li, Z.; Huang, Y. The recent progress of MXene-Based microwave absorption materials. *Carbon* **2021**, *174*, 484-499.

- [53] Cai, B.; Zhou, L.; Zhao, P. Y.; Peng, H. L.; Hou, Z. L.; Hu, P. F.; Liu, L. M.; Wang, G. S. Interface-induced dual-pinning mechanism enhances low-frequency electromagnetic wave loss. *Nat. Commun.* **2024**, *15*, 3299.
- [54] Zhang, Y.; Hu, P. F.; Zhao, P. Y.; Cai, B.; Peng, H. L.; Yang, S. H.; Koo, M. C.; Liang, C. M.; Wang, G. S. Phosphorus Vacancy-Induced Built-In Electric Field for Electromagnetic Properties Modulation. *Adv. Sci.* **2025**, *12*, e02857.
- [55] Wei, H.; Li, W. H.; Bachagha, K. Component optimization and microstructure design of carbon nanotube-based microwave absorbing materials: A review. *Carbon*, **2024**, *217*, 118651.
- [56] Micheli, D.; Apollo, C.; Pastore, R.; Marchetti, M. X-Band microwave characterization of carbon-based nanocomposite material, absorption capability comparison and RAS design simulation. *Compos. Sci. Technol.* **2010**, *70*, 400-409.
- [57] Sharma, S.; Parne, S. R.; Panda, S. S. S.; Gandhi, S. Progress in microwave absorbing materials: A critical review. *Adv. Colloid Interface Sci.* **2024**, *327*, 103143.
- [58] Fan, B. B.; Li, N.; Dai, B. Z.; Shang, S. Y.; Guan, L.; Zhao, B.; Wang, X. H.; Bai, Z. Y.; Zhang, R. Investigation of adjacent spacing dependent microwave absorption properties of lamellar structural $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes. *Adv. Powder Technol.* **2020**, *31*, 808-815.
- [59] Du, Y. Q.; Yan, Z. K.; You, W. B.; Men, Q. Q.; Chen, G. Y.; Lv, X. W.; Wu, Y. Y.; Luo, K. C.; Zhao, B. Z.; Zhang, J. C.; Che, R. C. Balancing MXene surface termination and interlayer spacing enables superior microwave absorption. *Adv. Funct. Mater.* **2023**, *33*, 2301449.
- [60] Zhang, J.; Jia, R.; Tan, K. B.; Li, J. M.; Xu, S. C.; Ying, G. B.; Han, W. J.; Lu, M. A review of MAX series materials: from diversity, synthesis, prediction, properties oriented to functions. *Nano-Micro Lett.* **2025**, *17*, 173.
- [61] Jia, L.; Zhou, S. Q.; Ahmed, A.; Yang, Z. C.; Liu, S. Q.; Wang, H.; Li, F.; Zhang, M.; Zhang, Y. J.; Sun, L. Y. Tuning MXene electrical conductivity towards multifunctionality. *Chem. Eng. J.* **2023**, *475*, 146361.
- [62] Wen, B.; Cao, M. S.; Hou, Z. L.; Song, W. L.; Zhang, L.; Lu, M. M.; Jin, H. B.; Fang, X. Y.; Wang, W. Z.; Yuan, J. Temperature dependent microwave attenuation behavior for carbon-nanotube/silica composites. *Carbon* **2013**, *65*, 124-139.
- [63] Wang, J. H.; Cai, B.; Sun, B. W.; Hou, Z. L.; Yang, S. H.; Yang, Q. L.; Zhao, P. Y.; Li, W. P.;

- Zhang, Y.; Wang, G. S. Molecular dipole engineering for tailored dielectric properties in MXene/ZnO heterostructures. *Acta Phys.-Chim. Sin.* **2026**, *42*, 100271.
- [64] Li, T.; Du, J. N.; Sun, J. X.; Liu, Q.; Li, X. R.; Ou, Y.; Qi, Q.; Liu, Y. N.; Meng, F. B. Bioinspired Free-Space Architecture Engineering for Broadband Electromagnetic Absorption and Thermal Management in Graphene-Based Fibrous Textiles. *Adv. Funct. Mater.* **2026**, *36*, e30666.
- [65] Chen, F.; Zhang, S. S.; Ma, B. B.; Xiong, Y.; Luo, H.; Cheng, Y. Z.; Li, X. C.; Wang, X.; Gong, R. Z. Bimetallic CoFe-MOF@Ti₃C₂T_x MXene derived composites for broadband microwave absorption. *Chem. Eng. J.* **2022**, *431*, 134007.
- [66] Cai, L.; Pan, F.; Zhu, X. J.; Dong, Y. Y.; Shi, Y. Y.; Xiang, Z.; Cheng, J.; Jiang, H. J.; Shi, Z.; Lu, W. Etching engineering and electrostatic self-assembly of N-doped MXene/hollow Co-ZIF hybrids for high-performance microwave absorbers. *Chem. Eng. J.* **2022**, *434*, 133865.
- [67] Wang, H. M.; Xiao, J. X.; Wu, Y. Z.; Yang, Z. Q.; Kan, X. C.; Ding, J. F.; Zhang, Z. Q.; Zhang, X. K.; Qi, X. S. Modulation of Built-In Electric Fields via Doping Strategy for Efficient Electromagnetic Response. *Adv. Funct. Mater.* **2026**, *36*, e76998.
- [68] Wu, T.; Ren, P. G.; Xue, S. F.; Wang, L. W.; Guo, Z. Z.; Wang, J. Q.; Zong, Z.; Huang, W.; Hou, X.; Ren, F. Dual-coupled interfaces drive defect-porosity synergy to enhance low-frequency electromagnetic wave absorption in MXene-based composites. *Chem. Eng. J.* **2025**, *526*, 171069.
- [69] Ye, X. Y.; Lv, Y. H.; Zhang, L.; Chen, H. X.; Chen, S.; Wu, Y. P.; Ma, L. A.; Wang, Q. T. Hierarchical carbon nanotubes-modified heterogeneous composites derived from melamine-mixed ZIF-67/MXene for broadband microwave absorption. *Carbon* **2024**, *216*, 118585.
- [70] Zia, T. H.; Gul, I. H.; Kebaili, I.; Alomayrah, N.; Ara, B.; Gul, K. Cole-Cole plot analysis of complex permittivity for investigating the dielectric relaxation process in polystyrene based high-k nanocomposite. *Mater. Chem. Phys.* **2025**, *343*, 131048.
- [71] He, M.; Lv, X. L.; Peng, H.; Zhou, Y. M.; Li, H. Y.; Li, Z. H.; Wang, Y. J.; Bu, X. H. Biomimetic artificial nacre-like microfiber of Co/C modified cellulose nanofiber/Ti₃C₂T_x MXene with efficient microwave absorption. *Chem. Eng. J.* **2024**, *491*, 151726.

- [72] Wang, X.; Pan, F.; Cai, L.; Cheng, J.; Jiang, H. J.; Yang, Y.; Guo, H. T.; Shi, Z.; Xiong, Z. M.; Xie, A. M.; Xu, H. Y.; Lu, W. Multifunctional ultralight magnetic CNFs/MXene/Fe₃O₄ nanodiscs aerogel with superior electromagnetic wave absorption performance. *Chem. Eng. J.* **2023**, *475*, 146319.
- [73] Limbrock, J. K.; Kemna, A. Relationship between Cole-Cole model parameters in permittivity and conductivity formulation. *Geophys. J. Int.* **2024**, *239*, 964-970.
- [74] Wang, X.; Pan, F.; Xiang, Z.; Zeng, Q. W.; Pei, K.; Che, R. C.; Lu, W. Magnetic vortex core-shell Fe₃O₄@C nanorings with enhanced microwave absorption performance. *Carbon* **2020**, *157*, 130-139.
- [75] Shao, C. Q.; Liu, H. G.; Shi, Y. Y.; Tian, N.; You, C. Y.; Zhao, Z. Y. Dielectric-magnetic synergy in ferrite/carbon composites for electromagnetic microwave absorption. *Nano Res.* **2025**, *18*, 94907815.
- [76] Hu, F. Y.; Wang, X. H.; Bao, S.; Song, L. M.; Zhang, S.; Niu, H. H.; Fan, B. B.; Zhang, R.; Li, H. X. Tailoring electromagnetic responses of delaminated Mo₂TiC₂T_x MXene through the decoration of Ni particles of different morphologies. *Chem. Eng. J.* **2022**, *440*, 135855.
- [77] Zeng, X. J.; Cheng, X. Y.; Yu, R.; H. Stucky, G. D. Electromagnetic microwave absorption theory and recent achievements in microwave absorbers. *Carbon* **2020**, *168*, 606-623.
- [78] Xiong, X. H.; Zhang, H. B.; Lv, H. L.; Yang, L. T.; Liang, G. S.; Zhang, J. C.; Lai, Y. X.; Cheng, H. W.; Che, R. C. Recent progress in carbon-based materials and loss mechanisms for electromagnetic wave absorption. *Carbon* **2024**, *219*, 118834.
- [79] Wang, X. Q.; Yan, H. Y.; Zhao, S. C.; Liu, S. Q.; Chang, H. Modifiable natural ferromagnetic resonance frequency and strong microwave absorption in BaFe_{12-y-2x}Al_ySn_xMn_xO₁₉ M-type hexaferrite. *J. Magn. Magn. Mater.* **2023**, *586*, 171159.
- [80] Hou, T. Q.; Jia, Z. R.; Dong, Y. H.; Liu, X. H.; Wu, G. L. Layered 3D structure derived from MXene/magnetic carbon nanotubes for ultra-broadband electromagnetic wave absorption. *Chem. Eng. J.* **2022**, *431*, 133919.
- [81] Wu, N. N.; Shen, Z. Y.; Ma, Y. T.; Wu, Z. Z.; Hou, C. X.; Guo, S. J.; Tian, J.; Liu, J. R. Three-dimensional lightweight melamine foams modified by MXene sheets and CoNi alloys towards multifunctional microwave absorption. *Nano Res.* **2025**, *18*, 94907121.
- [82] Liang, X. M.; Xuan, Q. F.; Li, H. H.; Ding, P. J.; Zhang, Y.; Koo, M. C.; Liang, C. M.; Yang,

- S. H.; Zhao, P. Y.; Zhang, D. F.; Wang, G. S. Multifunctional hierarchical BN/MXene-Fe₃O₄ aerogel for efficient thermal management and ultra-broadband microwave absorption. *Chem. Eng. J.* **2025**, *523*, 168409.
- [83] Kahmann, T.; Rösch, E. L.; Enpuku, K.; Yoshida, T.; Ludwig, F. Determination of the effective anisotropy constant of magnetic nanoparticles-Comparison between two approaches. *J. Magn. Magn. Mater.* **2021**, *519*, 167402.
- [84] Wang, X. W.; Zhao, C.; Li, C. P.; Liu, Y.; Sun, S.; Yu, Q. L.; Yu, B.; Cai, M. R.; Zhou, F. Progress in MXene-based materials for microwave absorption. *J. Mater. Sci. Technol.* **2024**, *180*, 207-225.
- [85] Liu, C. X.; Li, J. Z.; Li, S.; Guo, Z. Q.; Chen, Y.; Li, T.; Qin, R. C.; Sun, J. X.; Lu, Y. X.; Meng, F. B. Neural Network-Based Permittivity Engineering of Magnetic Absorbers for Customizable Microwave Absorption. *Adv. Sci.* **2026**, *13*, e21945.
- [86] Hou, Y. Z.; Liu, K. R.; Chen, J. S.; Wang, B.; He, X. C.; Li, D.; Wei, S. C.; Li, B. C.; Han, Q. Bimetallic MOFs/MXene derived CoNi@C@Ti₃C₂T_x/TiO₂ nanocomposites for high-efficiency electromagnetic wave absorption. *Carbon* **2024**, *216*, 118587.
- [87] Yu, M.; Huang, Y.; Liu, X. D.; She, K. H.; Zhao, X. X.; Fan, W. Q.; Ma, X. F.; Zou, J. H.; Li, T. H. Synthetic strategy of biomimetic sea urchin-like Co-NC@PANI modified MXene-based magnetic aerogels with enhanced electromagnetic wave absorption properties. *Nano Res.* **2024**, *17*, 2025-2037.
- [88] Sun, C. H.; Li, Q. Y.; Jia, Z. R.; Wu, G. L.; Yin, P. F. Hierarchically flower-like structure assembled with porous nanosheet-supported MXene for ultrathin electromagnetic wave absorption. *Chem. Eng. J.* **2023**, *454*, 140277.
- [89] Rasaili, P.; Sharma, N. K.; Bhattarai, A. Comparison of ferromagnetic materials: Past work, recent trends, and applications. *Condens. Matter* **2022**, *7*, 12.
- [90] Wang, H. T.; Feng, W.; Liu, D.; Zhang, G. D.; Liu, Y.; Wang, J.; Zou, L. Iron-based soft magnetic materials fabricated by laser additive manufacturing. *Eng. Sci.* **2023**, *22*, 809.
- [91] Yu, W. T.; Wang, Z. Q.; Lin, J. H.; Xiao, Y. S.; Zhu, L. Y.; Huang, J. T.; Pereira, A.; Guo, Z. H.; Min, Y. G. Rose-derived porous carbon and in-situ fabrication of cobalt/nickel nanoparticles composites as high-performance electromagnetic wave absorber. *Eng. Sci.* **2024**, *30*, 1113.

- [92] Monson, T. C.; Ma, Q.; Stevens, T. E.; Lavin, J. M.; Leger, J. L.; Klimov, P. V.; Huber, D. L. Implication of ligand choice on surface properties, crystal structure, and magnetic properties of iron nanoparticles. *Part. Part. Syst. Char.* **2013**, *30*, 258-265.
- [93] Li, X. H.; Guo, X. H.; Liu, T. C.; Zheng, X. L.; Bai, J. T. Shape-controlled synthesis of Fe nanostructures and their enhanced microwave absorption properties at L-band. *Mater. Res. Bull.* **2014**, *59*, 137-141.
- [94] Mudasar, M.; Hussain, B.; Lian, S.; Li, X.; Cheng, X. W. Design and radar stealth performance of high-efficiency Nb₂CT_x-MXene/ α -Fe Heterogeneous composites with synergistic magnetic-dielectric loss. *ACS Appl. Electron. Mater.* **2025**, *7*, 4557-4571.
- [95] Yang, P.-A.; Wang, L.; Ruan, H. B.; Deng, W. J.; Li, R.; Shou, M. J.; Huang, X.; Zhang, Y. X.; Lu, Y. Heterogeneous interface engineering and directional tuning electromagnetic parameters of MXene/Fe NPs absorbers for precise low-frequency microwave absorption. *Nano Res.* **2025**, *18*, 94907783.
- [96] Shan, B.; Wang, Y.; Ji, X. Y.; Huang, Y. Enhancing low-frequency microwave absorption through structural polarization modulation of MXenes. *Nano-Micro Lett.* **2024**, *16*, 212.
- [97] Mohapatra, J.; Xing, M.; Elkins, J.; Liu, J. P. Hard and semi-hard magnetic materials based on cobalt and cobalt alloys. *J. Alloys Compd.* **2020**, *824*, 153874.
- [98] Han, Y. X.; Yang, Y. R.; Li, T. H.; Zhang, Y. L.; Guo, H.; He, M. K.; Han, K. H.; Qiu, H.; Gu, J. W. Hierarchical Heterogeneous Co-based Magnetic Absorbers for Superior Broadband High-efficiency Microwave Absorption. *Adv. Funct. Mater.* **2025**, *36*, e25719.
- [99] Cai, B.; Zhou, L.; Zhao, P. Y.; Peng, H. L.; Hou, Z. L.; Hu, P. F.; Liu, L. M.; Wang, G. S. Interface-induced dual-pinning mechanism enhances low-frequency electromagnetic wave loss. *Nat. Commun.* **2024**, *15*, 3299.
- [100] Liao, T. H.; Li, T.; Zou, Y.; Ma, H. F.; Qian Yang, Q.; Luo, K.; Y.; Han, M. Y.; Meng, F. B. Bioinspired 4D-Printing Microwave Absorbers With Adaptive Programmable Switches via Morphable Percolation Networks and Resonant Models. *Adv. Mater.* **2026**, *38*, e73633.
- [101] Peng, Y. H.; Liu, J. R.; Feng, Z. B.; Peng, J. B.; Guo, Y. X.; Zhang, Y.; Fu, Y. J.; Liu, C. B.; Deng, L. B. Multi-component heterogeneous interface engineering and magnetic domain evolution for broadband electromagnetic wave attenuation. *Chem. Eng. J.* **2025**, *524*, 168991.
- [102] Pan, F.; Yu, L. Z.; Xiang, Z.; Liu, Z. C.; Deng, B. W.; Cui, E. B.; Shi, Z.; Li, X.; Lu, W.

- Improved synergistic effect for achieving ultrathin microwave absorber of 1D Co nanochains/2D carbide MXene nanocomposite. *Carbon* **2021**, *172*, 506-515.
- [103] Zou, Z.; Ning, M. Q.; Lei, Z. K.; Zhuang, X. H.; Tan, G. G.; Hou, J. H.; Xu, H.; Man, Q. K.; Li, J. B.; Li, R. W. 0D/1D/2D architectural Co@C/MXene composite for boosting microwave attenuation performance in 2–18 GHz. *Carbon* **2022**, *193*, 182-194.
- [104] Zhao, Y. Q.; Wang, J. J.; Yang, D. Y.; Du, Z.; Zhi, X. Y.; Yu, R. R.; Guo, Z. L.; Tang, C. C.; Fang, Y. MXene-CNTs/Co dielectric-electromagnetic synergistic composites with multi-heterogeneous interfaces for microwave absorption. *Carbon* **2025**, *232*, 119825.
- [105] Shu, R. W.; Yang, X. H.; Zhao, Z. W. Fabrication of core-shell structure NiFe₂O₄@SiO₂ decorated nitrogen-doped graphene composite aerogels towards excellent electromagnetic absorption in the Ku band. *Carbon* **2023**, *210*, 118047.
- [106] Zhao, T. B.; Jia, Z. R.; Zhang, Y.; Wu, G. L. Multiphase molybdenum carbide doped carbon hollow sphere engineering: the superiority of unique double - shell structure in microwave absorption. *Small*, **2023**, *19*, 2206323.
- [107] Zhang, Y.; Liu, X. H.; Guo, Z. Q.; Jia, C. Y.; Lu, F.; Jia, Z. R.; Wu, G. L. MXene@Co hollow spheres structure boosts interfacial polarization for broadband electromagnetic wave absorption. *J. Mater. Sci. Technol.* **2024**, *176*, 167-175.
- [108] Yu, L. Y.; Lan, D.; Guo, Z. Q.; Feng, A. L.; Wu, G. L.; Jia, Z. R.; Feng, X.; Yin, P. F. Multi-level hollow sphere rich in heterojunctions with dual function: Efficient microwave absorption and antiseptic. *J. Mater. Sci. Technol.* **2024**, *189*, 155-165.
- [109] Wu, Z.; Tan, X. L.; Wang, J. Q.; Xing, Y. Q.; Huang, P.; Li, B. J.; Liu, L. MXene hollow spheres supported by a C-Co exoskeleton grow MWCNTs for efficient microwave absorption. *Nano-Micro Lett.* **2024**, *16*, 107.
- [110] Li, N.; Xie, X.; Lu, H. X.; Fan, B. B.; Wang, X. H.; Zhao, B.; Zhang, R.; Yang, R. Novel two-dimensional Ti₃C₂T_x/Ni-spheres hybrids with enhanced microwave absorption properties. *Ceram. Int.* **2019**, *45*, 22880-22888.
- [111] Liu, Y.; Zhang, S.; Su, X. L.; Xu, J.; Li, Y. Y. Enhanced microwave absorption properties of Ti₃C₂ MXene powders decorated with Ni particles. *J. Mater. Sci.* **2022**, *55*, 10339-10350.
- [112] Wu, Y. P.; Chen, C. L.; Pan, F.; Li, X.; Lu, W. Interlayer growth of magnetic nanocomponent in Ti₃C₂T_x MXene EMW absorbers for periodic electromagnetic synergetic

- network. *Carbon* **2025**, *231*, 119741.
- [113] Wang, X.; Dong, G. L.; Pan, F.; Lin, C.; Yuan, B.; Yang, Y.; Lu, W. Metal-support interaction induced electron localization in rationally designed metal sites anchored MXene enables boosted electromagnetic wave attenuation. *Nano-Micro Lett.* **2025**, *17*, 309.
- [114] Wen, C. Y.; Li, X.; Zhang, R. X.; Xu, C. Y.; You, W. B.; Liu, Z. W.; Zhao, B.; Che, R. C. High-density anisotropy magnetism enhanced microwave absorption performance in $\text{Ti}_3\text{C}_2\text{T}_x$ MXene@Ni microspheres. *Acs Nano* **2021**, *16*, 1150-1159.
- [115] Zhao, B.; Li, Y.; Zeng, Q. W.; Wang, L.; Ding, J. J.; Zhang, R.; Che, R. C. Galvanic replacement reaction involving core-shell magnetic chains and orientation - tunable microwave absorption properties. *Small* **2020**, *16*, 2003502.
- [116] Pan, F.; Rao, Y. P.; Batalu, D.; Cai, L.; Dong, Y. Y.; Zhu, X. J.; Shi, Y. Y.; Shi, Z.; Liu, Y. W.; Lu, W. Macroscopic electromagnetic cooperative network-enhanced MXene/Ni chains aerogel-based microwave absorber with ultra-low matching thickness. *Nano-Micro Lett.* **2022**, *14*, 140.
- [117] Pathak, P.; Nartu, M. S. K. K. Additive manufacturing of soft magnetic high entropy alloys: A review. *J. Magn. Magn. Mater.* **2025**, *627*, 173148.
- [118] Chaudhary, V.; Chaudhary, R.; Banerjee, R.; Ramanujan, R. V. Accelerated and conventional development of magnetic high entropy alloys. *Mater. Today*, **2021**, *49*, 231-252.
- [119] Yakin, A.; Simsek, T.; Avar, B.; Simsek, T.; Chattopadhyay, A. K. A review of soft magnetic properties of mechanically alloyed amorphous and nanocrystalline powders. *Emergent Mater.* **2023**, *6*, 453-481.
- [120] Guo, Y. Q.; Li, P.; Zhao, R. L.; Gu, J. W. Preparation and mechanism of thermally conductive polyimide phase change composites with electromagnetic wave-absorbing performance. *Acta Polym. Sin.* **2025**, *56*, 2347-2360.
- [121] Li, X. S.; Xue, Z. Y.; Hou, X. B.; Wang, G. Q.; Huang, X.; Ke, H. B.; Sun, B. A.; Wang, W. H. FeCo-based amorphous alloys with high ferromagnetic elements and large annealing processing window. *Intermetallics* **2021**, *131*, 107087.
- [122] Rao, H. C.; Nan, K.; Wang, W.; Zhang, Y. K.; Wang, Y. Electrostatically self-assembled hierarchical magnetic $\text{Co}_7\text{Fe}_3\text{@C/Ti}_3\text{C}_2\text{T}_x$ nanocomposite for high-efficient microwave absorption. *Mater. Today Phys.* **2024**, *41*, 101355.

- [123] Li, X.; Wen, C. Y.; Yang, L. T.; Zhang, R. X.; Li, X. H.; Li, Y. S.; Che, R. C. MXene/FeCo films with distinct and tunable electromagnetic wave absorption by morphology control and magnetic anisotropy. *Carbon* **2021**, *175*, 509-518.
- [124] Wang, J. H.; Zhang, L.; Yan, J. F.; Yun, J. N.; Zhao, W.; Dai, K.; Wang, H.; Sun, Y. S. MXene-based ultrathin electromagnetic wave absorber with hydrophobicity, anticorrosion, and quantitatively classified electrical losses by intercalation growth nucleation engineering. *Adv. Funct. Mater.* **2024**, *34*, 2402419.
- [125] Shu, X. F.; Yan, S. C.; Liu, Y.; Min, F. F.; Fang, B.; Pan, L. K. Doping-engineered Fermi level modulation in MXenes: Multiphysics field coupling enabled electron-pathway design for electromagnetic optimization. *Chem. Eng. J.* **2025**, *524*, 169345.
- [126] Xiong, J.; Xiang, Z.; Zhao, J.; Yu, L. Z.; Cui, E. C.; Deng, B. W.; Liu, Z. C.; Lu, W. Layered NiCo alloy nanoparticles/nanoporous carbon composites derived from bimetallic MOFs with enhanced electromagnetic wave absorption performance. *Carbon* **2019**, *154*, 391-401.
- [127] Gao, X. R.; Jia, Z. R.; Wang, B. B.; Wu, X. M.; Sun, T.; Liu, X. H.; Chi, Q. G.; Wu, G. L. Synthesis of NiCo-LDH/MXene hybrids with abundant heterojunction surfaces as a lightweight electromagnetic wave absorber. *Chem. Eng. J.* **2021**, *419*, 130019.
- [128] Niu, W. H.; Pakhira, S.; Marcus, K.; Li, Z.; Mendoza-Cortes, J. L.; Yang, Y. Apically dominant mechanism for improving catalytic activities of N-doped carbon nanotube arrays in rechargeable zinc-air battery. *Adv. Energy Mater.* **2018**, *8*, 1800480.
- [129] Wu, T.; Ren, F.; Guo, Z. Z.; Zhang, J. L.; Hou, X.; Chen, Z. Y.; Jin, Y. L.; Ren, P. G. Bayberry-like bimetallic CoNi-MOF-74 derivatives/MXene hybrids with abundant heterointerfaces toward high-efficiency electromagnetic wave absorption. *J. Alloys Compd.* **2024**, *976*, 172984.
- [130] Chen, M.; Zhao, G.; Shao, L. L.; Yuan, Z. Y.; Jing, Q. S.; Huang, K. J.; Huang, Z. Y.; Zhao, X. H.; Zou, G. D. Controlled synthesis of nickel encapsulated into nitrogen-doped carbon nanotubes with covalent bonded interfaces: the structural and electronic modulation strategy for an efficient electrocatalyst in dye-sensitized solar cells. *Chem. Mater.* **2017**, *29*, 9680-9694.
- [131] Wang, B. J.; Xu, Z. J.; Wu, H.; Huang, F. Z.; Liu, F. H.; Li, S. K.; Zhang, H.

- Architecture-inspired N-doped carbon nanotube bridging well-arranged MXene nanosheets toward efficient electromagnetic wave absorption. *Compos. Part B* **2023**, 257, 110669.
- [132] Zeng, X.; Zhao, C.; Nie, T.; Shen, Z.-Y.; Yu, R.; Stucky, G. D. Construction of 0D/1D/2D MXene nanoribbons-NiCo@NC hierarchical network and their coupling effect on electromagnetic wave absorption. *Mater. Today Phys.* **2022**, 28, 100888.
- [133] Feng, Y. B.; Qiu, T. Preparation, characterization and microwave absorbing properties of FeNi alloy prepared by gas atomization method. *J. Alloys Compd.* **2012**, 513, 455-459.
- [134] Lin, S.; Lin, J.; Xiong, Z. Q.; He, X.; Li, X.; Liu, C. B.; Wang, C. Y.; Zeng, X. J.; Nie, X. L.; Che, R. C. Micro-helical Ni₃Fe chain encapsulated in ultralight MXene/C aerogel to realize multi-functionality: radar stealth, thermal insulation, fire resistance, and mechanical properties. *Chem. Eng. J.* **2024**, 492, 152248.
- [135] Li, H.; Li, H. Y.; Shen, Z. F.; Zeng, S. T.; Yang, F.; Cai, Q.; Xu, W. Q.; Luo, C.; Liu, Y. In-situ deposition and comparative study of electromagnetic absorption performance of MXene (Ti₃C₂T_x)@nano-Fe₁Co_{0.8}Ni₁ composites with different compositions. *Int. J. Miner. Metall. Mater.* **2025**, 32, 1259-1269.
- [136] Xie, X. B.; Wang, B. L.; Wang, Y. K.; Ni, C.; Sun, X. Q.; Du, W. Spinel structured MFe₂O₄ (M = Fe, Co, Ni, Mn, Zn) and their composites for microwave absorption: A review. *Chem. Eng. J.* **2022**, 428, 131160.
- [137] Tian, N.; Wang, C. K.; You, C. Y. Synthesis of nanospherical CoFe₂O₄/Ti₃C₂T_x MXene composites with enhanced microwave absorbing performance. *J. Alloys Compd.* **2023**, 967, 171796.
- [138] Wang, Q.; Liu, X. J.; Cui, J.; Yan, Y. H. Gradient and flexible poly (vinylidene fluoride) composite with synergistically enhanced wave absorption performance by MXene and hollow cobalt ferrite. *Chem. Eng. J.* **2025**, 520, 165961.
- [139] Nguyen, M. D.; Tran, H.-V.; Xu, S. J.; Lee, T. R. Fe₃O₄ nanoparticles: structures, synthesis, magnetic properties, surface functionalization, and emerging applications. *Appl. Sci.* **2021**, 11, 11301.
- [140] Xiang, Z.; Song, Y. M.; Xiong, J.; Pan, Z. P.; Wang, X.; Liu, L.; Liu, R.; Yang, H. W.; Lu, W. Enhanced electromagnetic wave absorption of nanoporous Fe₃O₄@carbon composites derived from metal-organic frameworks. *Carbon* **2019**, 142, 20-31.

- [141] Deng, Y. F.; Zheng, Y.; Zhang, D. F.; Han, C. A.; Cheng, A.; Shen, J. Y.; Zeng, G. X.; Zhang, H. Y. A novel and facile-to-synthesize three-dimensional honeycomb-like nano-Fe₃O₄@C composite: Electromagnetic wave absorption with wide bandwidth. *Carbon* **2020**, *169*, 118-128.
- [142] Li, Q. W.; Nan, K.; Wang, W.; Zheng, H.; He, K. K.; Wang, Y. Electrostatically fabricated heterostructure of interfacial-polarization-enhanced Fe₃O₄/C/MXene for ultra-wideband electromagnetic wave absorption. *J. Colloid Interface. Sci.* **2024**, *662*, 796-806.
- [143] Cui, Y. H.; Yang, K.; Wang, J. Q.; Shah, T.; Zhang, Q. Y.; Zhang, B. L. Preparation of pleated RGO/MXene/Fe₃O₄ microsphere and its absorption properties for electromagnetic wave. *Carbon* **2021**, *172*, 1-14.
- [144] Wangchhuk, J.; Meher, S. R. Structural, electronic and magnetic properties of inverse spinel NiFe₂O₄: DFT+U investigation. *Phys. Lett. A* **2022**, *443*, 128202.
- [145] Yuan, M.; Zhou, M.; Fu, H. Q. Synergistic microstructure of sandwich-like NiFe₂O₄@SiO₂@MXene nanocomposites for enhancement of microwave absorption in the whole Ku-band. *Compos. Part B* **2021**, *224*, 109178.
- [146] Noreen, S.; Hussain, A.; Tahir, M. B.; Ziya, A. B.; Rehman, J. U.; Usman, M.; Khan, S. A.; Akhtar, S. Structural, mechanical, thermodynamic, electronic, magnetic and optical properties of ZnFe₂O₄ ferrite: a DFT study. *Opt. Mater.* **2022**, *133*, 112930.
- [147] Xu, J.; Ma, W. J.; He, P.; Zhou, Y. K.; Liu, X. Y.; Chen, Y.; Zuo, P. Y.; Zhuang, Q. X. A water-induced self-assembly approach to 3D hierarchical magnetic MXene networks for enhanced microwave absorption. *J. Mater. Chem. A* **2023**, *11*, 330-340.
- [148] Salih, A. T.; Lafta, S. H.; Najim, A. A.; Mahmood, N. B.; Salman, G. K. Structural, morphological and electrical properties of α -Fe₂O₃ nanoparticles prepared by chemical route. *Ceram. Int.* **2025**, *51*, 25250-25257.
- [149] Chen, Y.; Hu, F. Y.; Cui, X. H.; Zhang, P. G.; Zhang, H. Q.; Chang, S. Q.; Hu, X. D.; Zhang, X. H. Nano metal oxide-intercalated MXene in-situ prepared by irradiation as effective electromagnetic wave absorbents. *2D Mater.* **2023**, *10*, 035014.
- [150] Huang, M. H.; Zhao, K.; Liu, S. Y.; Bian, A.; Jiang, L.; He, D. W.; He, J. Q.; Wang, Y. S. MOF derived α -Fe₂O₃/Ti₃C₂T_x magnetic-dielectric composites for microwave absorption. *J. Phys. Chem. Solids* **2024**, *188*, 111893.

- [151] Mei, J.; Liao, T.; Ayoko, G. A.; Bell, J.; Sun, Z. Q. Cobalt oxide-based nanoarchitectures for electrochemical energy applications. *Prog. Mater. Sci.* **2019**, *103*, 596-677.
- [152] Santos, R. V.; Cabrera-Pasca, G. A.; Costa, C. S.; Bosch-Santos, B.; Otubo, L.; Pereira, L. F. D.; Correa, B. S.; Effenberger, F. B.; Burimova, A.; Freitas, R. S.; Carbonari, A. W. Crystalline and magnetic properties of CoO nanoparticles locally investigated by using radioactive indium tracer. *Sci. Rep.* **2021**, *11*, 21028.
- [153] Zhang, Q.; Xu, D. W.; Si, Y. F.; Xu, R. X.; Luo, B. L.; He, S. Y.; Liu, D. Ti₃C₂T_x MXene Nanosheets Decorated with Magnetic Co Nanoparticles and CoO Nanosheets for Microwave Absorption. *ACS Appl. Nano Mater.* **2022**, *5*, 7175-7186.
- [154] Yu, L. Y.; Zhu, Q. Q.; Guo, Z. Q.; Cheng, Y. H.; Jia, Z. R.; Wu, G. L. Unique electromagnetic wave absorber for three-dimensional framework engineering with copious heterostructures. *J. Mater. Sci. Technol.* **2024**, *170*, 129-139.
- [155] Venkatanarayanan, A.; Spain, E. Review of recent developments in sensing materials. *Comprehensive Materials Processing* **2014**, *13*, 47-101.
- [156] Cai, Z.; Ma, Y. F.; Zhao, K.; Yun, M. C.; Wang, X. Y.; Tong, Z. M.; Wang, M.; Suhr, J.; Xiao, L. T.; Jia, S. T.; Chen, X. Y. Ti₃C₂T_x MXene/graphene oxide/Co₃O₄ nanorods aerogels with tunable and broadband electromagnetic wave absorption. *Chem. Eng. J.* **2023**, *462*, 142042.
- [157] Deng, R. X.; Chen, B. B.; Li, H. G.; Zhang, K.; Zhang, T.; Yu, Y.; Song, L. X. MXene/Co₃O₄ composite material: stable synthesis and its enhanced broadband microwave absorption. *Appl. Surf. Sci.* **2019**, *488*, 921-930.
- [158] Zeng, X. J.; Zhao, C.; Yin, Y. C.; Nie, T. L.; Xie, N. H.; Yu, R. H.; Stucky, G. D. Construction of NiCo₂O₄ nanosheets-covered Ti₃C₂T_x MXene heterostructure for remarkable electromagnetic microwave absorption. *Carbon* **2022**, *193*, 26-34.
- [159] Bao, Y. F.; Wang, W. R.; Liu, Y.; Yue, Z. H.; Guo, S. Y. Self-assembly Ti₃C₂T_x MXene/ZnCo₂O₄@ZnO heterostructure with Schottky junction for regulating BIEF to enhance microwave absorption. *Appl. Surf. Sci.* **2025**, *680*, 161393.
- [160] Gao, T. Y.; Li, Y.; Lai, C. W.; Xiang, P.; Badruddin, I. A.; Dhiman, P.; Kumar, A. Recent advances in transition metal Dichalcogenide-Based electrodes for asymmetric supercapacitors. *Catalysts* **2025**, *15*, 945.

- [161] Ha, J. H.; Park, G. B.; Kang, G. H.; Kang, J. O.; Bak, H. J.; Lee, D. J.; Lee, H. J.; Cho, K. H.; Kim, Y. S. Recent advances in tuning the properties of metallic 2D transition-metal dichalcogenides for energy conversion and storage. *Adv. Ind. Eng. Chem.* **2026**, *2*, 5.
- [162] Hu, H.; Wang, Z. Y.; Pan, M. L.; Chen, Y. M.; Han, Y. X.; Wang, J. D. Interface Effects in Metal-2D TMDs Systems: Advancing the Design and Development Electrocatalysts. *Adv. Sci.* **2025**, *12*, 2500226.
- [163] Gopika, M. S.; Savitha Pillai, S. Impact of morphology on the magnetic and optical properties of cobalt sulfide. *J. Mater. Res.* **2023**, *38*, 2097-2111.
- [164] Liu, Z. Y.; Wu, C. M.; Wang, Y.; Xian, G. Y.; Zhu, Z. L.; Xie, N.; Wang, Y. F.; Liu, Y.; Kong, L. L. MXene/CoS heterostructures self-assembled through electrostatic interaction as superior microwave absorber. *J. Alloys Compd.* **2022**, *900*, 163452.
- [165] Huo, Y. S.; Zhang, L.; Tan, Y. J.; Liu, Y.; Wang, M. J.; Zhao, M. S.; Huo, S. Y.; Gao, P.; Jin, Q.; He, Z. H. Multidimensional CoS₂/C/MXene nanofiber heterostructures with synergistic magnetic-dielectric coupling for ultra-strong and broadband microwave absorption. *Appl. Mater. Today* **2026**, *48*, 103029.
- [166] Wang, C. T.; Pang, X. X.; Wang, G. Q.; Gao, L. J.; Fu, F. Cobalt sulfide (Co₉S₈)-based materials with different dimensions: Properties, preparation and applications in photo/electric catalysis and energy storage. *Photochem* **2023**, *3*, 15-37.
- [167] Hou, T. Q.; Jia, Z. R.; Wang, B. B.; Li, H. B.; Liu, X. H.; Bi, L.; Wu, G. L. MXene-based accordion 2D hybrid structure with Co₉S₈/C/Ti₃C₂T_x as efficient electromagnetic wave absorber. *Chem. Eng. J.* **2021**, *414*, 128875.
- [168] Shombe, G. B.; Khan, M. D.; Zequine, C.; Zhao, C.; Gupta, R. K.; Revaprasadu, N. Direct solvent free synthesis of bare α -NiS, β -NiS and α - β -NiS composite as excellent electrocatalysts: Effect of self-capping on supercapacitance and overall water splitting activity. *Sci. Rep.* **2020**, *10*, 3260.
- [169] Chang, M.; Jia, Z. R.; He, S. Q.; Zhou, J. X.; Zhang, S.; Tian, M. L.; Wang, B. B.; Wu, G. L. Two-dimensional interface engineering of NiS/MoS₂/Ti₃C₂T_x heterostructures for promoting electromagnetic wave absorption capability. *Compos. Part B* **2021**, *225*, 109306.
- [170] Li, S. S.; Tang, X. W.; Zhao, X.; Lu, S. J.; Luo, J. T.; Chai, Z. Y.; Ma, T. T.; Lan, Q. Q.; Ma, P. M.; Dong, W. F.; Wang, Z. C.; Liu, T. X. Hierarchical graphene@MXene composite foam

- modified with flower-shaped FeS for efficient and broadband electromagnetic absorption. *J. Mater. Sci. Technol.* **2023**, *133*, 238-248.
- [171] Ali, S.; Bakhtiar, S. U. H.; Ismail, A.; Ismail, P. M.; Hayat, S.; Zada, A.; Wu, X. Q.; Alodhayb, A. N.; Zahid, M.; Raziq, F.; Yi, J. B.; Qiao, L. Transition metal sulfides: From design strategies to environmental and energy-related applications. *Coord. Chem. Rev.* **2025**, *523*, 216237.
- [172] Pan, F.; Wu, X. F.; Batalu, D.; Lu, W., Guan, H. T. Assembling of low-dimensional aggregates with interlaminar electromagnetic synergy network for high-efficient microwave absorption. *Adv. Powder Mater.* **2023**, *2*, 100100.
- [173] Fang, X.; Lin, Y. B.; Ma, J.; Huang, Y. Q.; Yu, K. H.; Zhong, B.; Yu, Y. L.; Li, N.; Qiang, L. Enhanced electromagnetic wave absorption performance of MXene@CuCo₂S₄ heterostructures achieved by optimizing flower-like CuCo₂S₄ configuration. *Appl. Surf. Sci.* **2025**, *716*, 164722.
- [174] Zhao, M. Y.; Zhang, B. F.; Li, Y.; Li, Y. X.; Kubuki, S.; Zhang, L.; Yong, Y. C. Tailoring the d-band electronic structure of metal sites to regulate oxidation pathways for advanced contaminant elimination. *Chem. Eng. J.* **2025**, *523*, 168432.
- [175] Yang, J. W.; Guo, Z. Z.; Cao, Y. Y.; Xin, J. L.; Chen, G. Anchoring nanoflower-like NiCoMoS on hierarchical MXene for enhanced electromagnetic wave absorption by the synergy of multiple losses mechanisms. *Mater. Today Phys.* **2025**, *59*, 101920.
- [176] Li, Q. W.; Nan, K.; Wang, W.; Zheng, H.; He, K. K.; Wang, Y. Electrostatically fabricated heterostructure of interfacial-polarization-enhanced Fe₃O₄/C/MXene for ultra-wideband electromagnetic wave absorption. *J. Colloid Interface Sci.* **2024**, *662*, 796-806.
- [177] Zhang, Y. L.; Ruan, K. P.; Zhou, K.; Gu, J. W. Controlled Distributed Ti₃C₂Tx Hollow Microspheres on Thermally Conductive Polyimide Composite Films for Excellent Electromagnetic Interference Shielding. *Adv. Mater.* **2023**, *35*, 2211642.
- [178] Dhamodharan, D.; Al-Harathi, M. A.; Ramya, B.; Bafaqeer, A.; Bafaqeer, A.; Alam, F. MXenes: a promising material with multifunctional applications. *J. Environ. Chem. Eng.* **2024**, *12*, 112316.
- [179] Sahoo, P.; Saini, L.; Dixit, A. Microwave-absorbing materials for stealth application: a holistic overview. *Oxford Open Mater. Sci.* **2023**, *3*, itac012.