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*REVIEWARTICLE – MATERIAL SCIENCE (MISCELLANEOUS)*

# A Review of Recent Advances in MXene-based Electromagnetic Shielding Materials: Structural Design Perspectives

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**Abstract**

The widespread adoption of 5G technology has exacerbated electromagnetic pollution due to the extensive deployment of high-frequency, energy-intensive electronic devices. This has, in turn, heightened the demand for the development of high-performance electromagnetic shielding materials. MXenes, a novel class of two-dimensional materials, exhibit exceptional electrical conductivity (>10,000 S/m) and tunable surface chemistry, making them ideal candidates for shielding applications. This article systematically reviews MXene synthesis methods, analyzes their advantages and limitations, and elucidates their electromagnetic shielding mechanisms dominated by interfacial polarization and conductive network formation. We critically evaluate global advancements in MXene-based architectures, including porous foams and hybrid composites with graphene/CNTs. Finally, we identify key challenges in balancing electrical conductivity with dispersion stability during scalable manufacturing and propose strategies to improve environmental durability through surface passivation and atomic-layer-deposited encapsulation.



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**Keywords**: MXenes; Electromagnetic Interference; Structural Design.

## 1. Introduction

With the rapid evolution of wireless communication technologies, particularly the global deployment of 5G networks (6G research is already underway), the operating frequency of electronic devices has escalated into the GHz range. While these devices greatly enhance convenience, their electromagnetic radiation poses a risk of electromagnetic interference (EMI) [1-3]. This interference not only accelerates the degradation of electronic components but also threatens human health, both physically and mentally [4 5]. Conventional metal-based shields face fundamental limitations in next-generation applications. Their high mass density conflicts with lightweighting requirements in aerospace and portable electronics, while galvanic corrosion in humid environments compromises durability. In addition, poor mechanical flexibility limits conformal coating on curved surfaces, and eddy current losses at high frequencies (>10 GHz) significantly degrade shielding efficiency (SE) by 40-60% [6]. These intrinsic shortcomings have led to intensive research into advanced materials that combine ultralight architectures, corrosion resistance and tunable electromagnetic properties [7].

MXenes, a unique class of two-dimensional materials primarily composed of transition metal carbides, nitrides, or carbonitrides, have emerged as promising candidates for efficient EMI shielding. First discovered by Yury Gogotsi in 2011, MXenes possess the key properties required for effective shielding [8-10]. The typical chemical formula of MXenes is $M_{n+1}X_nT_n$, where M stands for early transition metals, X represents carbon and/or nitrogen, and Tx refers to surface termination groups such as -OH, -O-, or -F [11-13] . To date, over 30 distinct MXenes materials have been extensively investigated and documented in the literature. Moreover, theoretical calculations have identified more than 130 potential MXene compositions, highlighting the vast compositional diversity within this class of materials [14] .

This review provides an overview of the preparation methods of MXenes and their respective advantages and disadvantages, as well as their electromagnetic shielding mechanisms. It also highlights significant research progress in the electromagnetic shielding application of $Ti_3C_2T_x$ MXene, particularly from a structural perspective. Critically, the future development of MXene-based EMI shielding materials requires dual breakthroughs in performance optimization and safety compliance: (1) Manufacturing process standardization must establish industrial-scale protocols aligned with WHO EMF exposure thresholds (<10 W/m² @2-300 GHz)[15] and EPA material attenuation criteria (ANSI C63.19-2019)[16]; (2) Material design should integrate environmental safety factors, such as passing biodegradability tests specified in IEC 62305-4:2021[17], to mitigate ecosystem risks throughout the life cycle; (3) Development of adaptive dynamic shielding mechanisms capable of maintaining compliance with ICNIRP 2020 public health protection guidelines[5] under extreme EMI conditions (>40 dB, per IEEE Std 299.1-2023[18]).

| **Nomenclature & Symbols** | | | |
|---|---|---|---|
| EMI | Electromagnetic Interference | HF | Hydrofluoric Acid |
| HCl | Hydrochloric Acid | LiF | Lithium Fluoride |
| DMSO | Dimethylsulfoxide | $NH_4HF_2$ | Ammonium Hydrogen Fluoride |
| SE | Shielding Effectiveness | T | Transmission Coefficient |
| R | Reflection Coefficient | A | Absorption Coefficient |
| SET | Total Shielding Effectiveness | MOF | MXene/Metal-Organic Framework |

## 2. Preparation of MXenes

MXenes are layered materials where the M (transition metal) and X (carbon/nitrogen) atoms are alternately arranged, obtained by selectively etching the A (typically aluminum) atomic layers from the MAX. The most common methods for preparing MXene nanosheets are the hydrofluoric acid (HF) etching method and the etching method using a mixture of hydrochloric acid (HCl) and fluoride salts. These preparation methods can significantly influence the types and content of surface functional groups, the layered structure, and the overall properties of the MXene nanosheets.

### *2.1. HF etching*

In 2011, Naguib [8] et al. obtained $Ti_3C_2T_x$ MXene by etching off the Al layer in $Ti_3AlC_2$ by HF, and the etching principle is shown in Fig.1. However, since the MXenes lamellae prepared by this method often contain certain holes, which will adversely affect its application, and the HF solution is more toxic and corrosive, the preparation process is prone to hazards and environmental issues. Additionally, the experimental parameters, such as temperature, HF mass concentration, and reaction time, are not easily controllable, so there is a need to find a versatile and relatively mild alternative. Therefore, it is necessary to find a universal, relatively mild, and environmentally friendly material to replace HF for the preparation of MXenes.

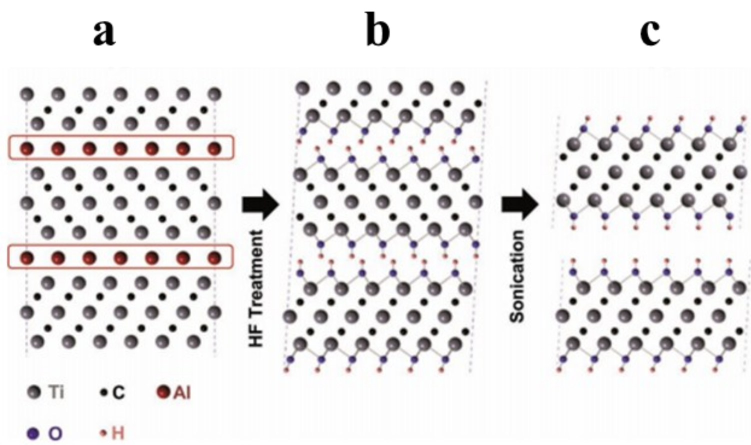



Fig. 1. Schematic illustration of the exfoliation process for $Ti_3AlC_2$, (a) The crystalline structure of pristine $Ti_3AlC_2$, (b) Substitution of Al atoms by hydroxyl groups via selective etching with HF, (c) Separation of MXene nanosheets through ultrasonic cleavage of hydrogen bonds in methanol medium [8], Copyright 2011, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

### *2.2. Hydrochloric acid (HCl) and fluoride in-situ etching*

Etching MAX by in-situ generated hydrofluoric acid yields MXenes with a more uniformly dispersed layer structure. Ghidiu [19] et al. in 2014 used a mixed solution of lithium fluoride (LiF) and HCl instead of HF as etchant.This method avoided the relatively dangerous HF in favor of the milder LiF and HCl. The introduction of LiF resulted in spontaneous intercalation of Li+ in MXenes, which significantly reduced the interlayer interaction force of the Ti3C2Tx MXene, and after exfoliation, it is easy to obtain single or few layers of Ti3C2Tx MXene. This preparation method is milder, with lower experimental risk, and the prepared MXene has a better delamination effect, large lateral size and better overall performance, which is a more common approach for the preparation of MXenes at present.

### *2.3. Molten fluoride salt etching*

In addition to aqueous solution etching, molten fluorine salts can also be used for etching to prepare MXenes. The reaction principle is essentially the same as the solution method, where F reacts with the atoms of the A-layer in the fluorine-containing molten salts. Under high temperature and high concentration conditions, few-layer or monolayer MXenes nanosheets can be obtained. However, the molten salt method also has some obvious drawbacks: impurities will be generated in the experiment, these impurities are difficult to remove, and the purity and crystallinity of the product cannot be well guaranteed, which will affect its performance and application [20].

### *2.4. Other methods*

There are many other ways to prepare MXenes, such as etching with sodium hydroxide and sulfuric acid [21, 22]. In 2013, Mashtalir et al [23] first used dimethylsulfoxide (DMSO) as an intercalating agent inserted into f- $Ti_3C_2$, and then ultrasonicated in water to strip f- $Ti_3C_2$ to form a stable colloidal solution, and MXenes were obtained by filtration. Given the high surface activity of MXenes, they exhibit significant adsorption properties, and the use of the solution etching method introduces trace amounts of water, which is unfavorable for applications in water-sensitive areas. Natu [24] used polar organic solvents instead of aqueous fluorine-containing solutions for the etching effect. Ammonium hydrogen fluoride ($NH_4HF_2$) dissolved in the organic solvent decomposed into HF and $NH_4F$, which could etch the A layer to form terminal fluorinated MXenes. Meanwhile, the $Ti_3C_2T_x$ MXene obtained by this method has a better performance in sodium ion storage compared with $Ti_3C_2T_x$ MXene prepared by the conventional aqueous phase etching method. The etching effect is shown in Fig.2.

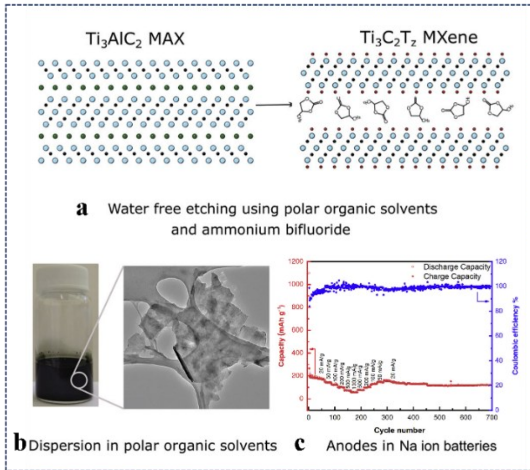



Fig. 2. (a) Selective chemical etching via polar aprotic solvents and ammonium hydrogen fluoride ($NH_4HF_2$) under water-free conditions, (b) Colloidal dispersion and stable suspension preparation through ultrasonic-assisted processing in polar solvents, (c) Integration of electrode components as high-capacity anode materials in sodium-ion batteries [24], Copyright 2020, Elsevier Inc.

### 3. Electromagnetic Shielding Mechanism

Electromagnetic shielding is a technical approach that utilizes shielding materials to obstruct electromagnetic wave transmission, with its fundamental principle being the creation of protective barriers to prevent electromagnetic radiation from penetrating designated spaces. This technology also serves as a crucial engineering solution for controlling electromagnetic interference phenomena. Usually, the shielding material works through reflection, absorption, multiple reflections, and other effects to attenuate incident wave energy [25]. The shielding mechanism is shown in Fig. 3. The shielding effectiveness (SE) is quantified by three key coefficients: transmission coefficient (T), reflection coefficient (R), and absorption coefficient (A), with the relationship A + R + T = 1. The total shielding effectiveness (SET) is expressed as the sum of three components [26-28]:

$$SE_T = SE_R + SE_A + SE_M \tag{1}$$

$$SE_A = -10 \log\frac{T}{(1-R)} \tag{2}$$

$$SE_R = -10 \log (1-R) \tag{3}$$

Here, SET, SER, SEA, and SEM stand for the total EMI shielding effectiveness, reflection loss, absorption loss, and multiple reflection loss respectively. In the process of EMI shielding, reflection loss occurs at the surface of the material, while absorption loss and multiple reflection loss are associated with interactions between interfaces within the material. Shielding materials typically contain a large number of positive and negative charge carriers, whose distribution is significantly influenced by the electromagnetic field. This interaction manifests as polarization, magnetization, and electrical effects. Absorption loss results from the interaction between dipoles in the material and the electromagnetic field, converting electromagnetic wave energy into thermal energy through dissipation. Absorption loss occurs within the material and depends on the frequency, electrical conductivity and magnetic permeability of the shielding material, independent of the type of electromagnetic wave. Higher values of these parameters generally lead to greater absorption loss. Reflection loss, on the other hand, arises from the mutual inductance between the magnetic and electrical conductors in the shielding material and the incident electromagnetic wave. When the impedance of the shielding material does not match that of the surrounding medium, it results in electromagnetic wave reflection[29, 30].

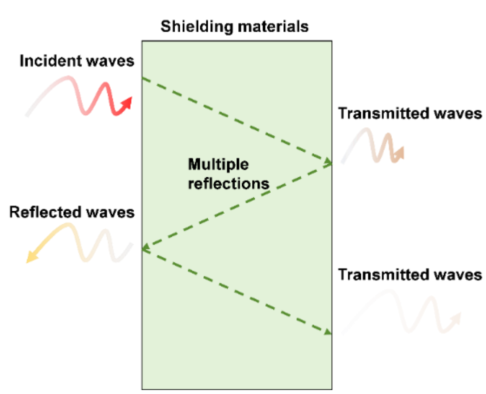


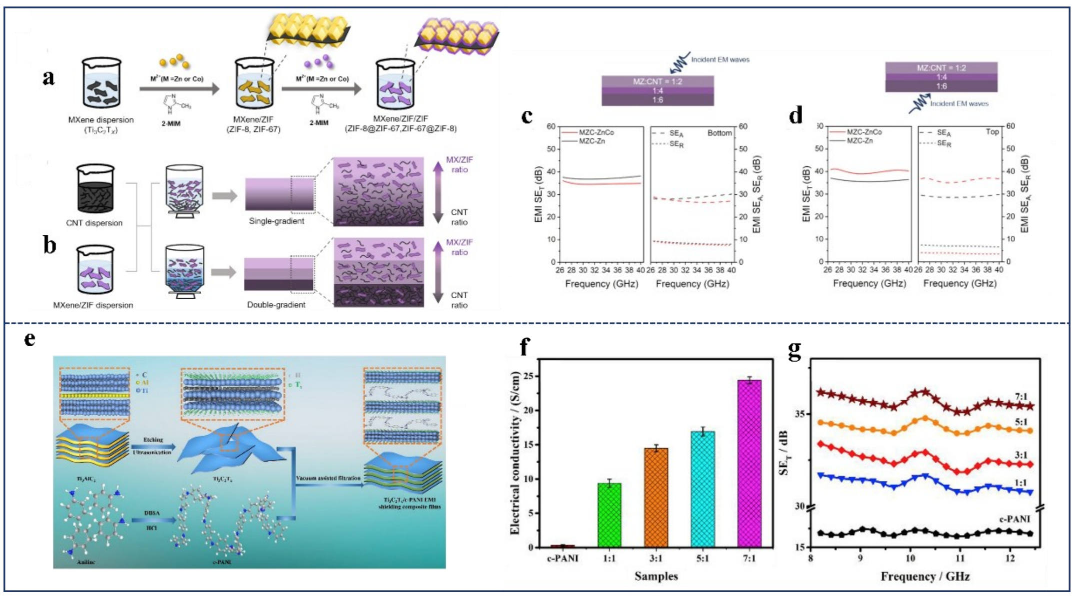

Fig. 3. The shielding mechanism of shielding materials

## 4. MXene-Based Electromagnetic Protection Materials

### *4.1. $Ti_3C_2T_x$ MXene-based randomly dispersed structural materials*

By simply mixing MXenes with a polymer matrix, a randomly dispersed structure can be obtained. Randomly dispersed MXenes structures are easily composited with carbon nanotubes, metal-organic frameworks, conductive polymers and other materials to form multifunctional composites. This composite structure not only enhances the electromagnetic shielding effect but also improves the material's mechanical properties and environmental stability[31, 32].

Cai et al [33] synthesized MXene/porous graphene (MX/HG) composite films using vacuum-assisted filtration. Through controlling the size of MXenes flakes and the content of HG, the L-MX/ HG films exhibit 9800 $S \cdot m^{-1}$ conductivity, with 56.15 dB EMI shielding effectiveness (SE), and a thickness of just 5 μm. The mechanical strength of the MX/HG film is significantly enhanced, with tensile stress reaching 120 MPa, owing to the formation of hydrogen bonds between the MXene sheets and HG. Jang et al [34] prepared a gradient-structured MXene/metal-organic framework (MOF)/carbon nanotubes (CNTs) composite film. Excellent electromagnetic shielding performance (40 dB) and electromagnetic wave absorption efficiency (42%) were achieved by reversing the concentration ratio of MXene/MOF/CNTs in the film thickness direction (Fig. 4a-d). Zhang et al [35] synthesized Ti3C2Tx MXene/co-doped polyaniline (Ti3C2Tx/c-PANI) EMI shielding composite films. Layer-by-layer (LbL) self-assembly enabled precise thickness control (40 μm ±1.2 μm) through electrostatic adsorption, overcoming limitations of solution casting methods." And DFT calculations confirmed that a 7:1 mass ratio maximizes hydrogen bond density between MXene edge $-NH_2$ groups and c-PANI quinoid structures, achieving peak carrier mobility; the integration of MXene's two-dimensional conductive network with c-PANI's chain-like aggregation has been demonstrated to enhance EMI SE and tensile strength. The conductivity is 24.4 $S \cdot cm^{-1}$, EMI SE is 36 dB, and tensile strength is 19.9 MPa; they are 81, 2.3, and 7.7 times higher than those in the pure c-PANI film (Fig. 4e-g).



Fig, 4. (a) Schematic diagram of the synthesis of MXene/ZIF, (b) Gradient-structured MXene/MOF/CNF for absorption-enhanced electromagnetic interference shielding, (c, d) EMI shielding effectiveness of MZC-Zn and MZC-ZnCo measured from the (c) top and (d) bottom [34], Copyright 2024, Elsevier Inc. (e) Fabrication of the $Ti_3C_2T_x$ /c-PANI films, (f) Electrical conductivity, (g) $SE_T$ of pure c-PANI film and $Ti_3C_2T_x$ /c-PANI films[35], Copyright 2019, Elsevier Ltd.

### *4.2. $Ti_3C_2T_x$ MXene-based thin film materials*

The exceptional electromagnetic interference shielding performance of MXene-based composite films is attributed to their high conductivity and the unique layered structure formed by the arrangement of two-dimensional sheets. Since the impedance mismatch at heterogeneous interfaces generates reflection losses and absorption losses inside MXene-based composites, constructing MXene-based composite films with complex internal structures is an effective method to prolong the transmission path of electromagnetic waves within the material, thus enhancing EMI shielding effectiveness.

Jahanger et al [36] prepared composite films with different $Ti_3C_2T_x$ MXene contents by solution casting method and systematically investigated their microstructures, mechanical properties and EMI shielding performance. The findings demonstrate that incorporating MXenes significantly enhances both conductivity and shielding effectiveness. When the $Ti_3C_2Tx$ MXene content reached 80 wt%, the EMI shielding effectiveness peaked at 34.80 dB. Bai et al [37]prepared a nanosheet-AgNW-based composite transparent conductive film (TCF) using PU as a substrate. The films were exposed to accelerated aging tests under conditions of relative humidity (RH) of 85% ± 5%. The films exhibited distinct humidity sensitivity, with the spacing between the MXene (002) planes increasing from 9.8 Å to 12.3 Å when the RH was greater than 60%. This expansion disrupts the conductive networks within the films. Furthermore, the incorporation of an Al2O3 encapsulation layer, achieved via atomic layer deposition (ALD), led to an enhancement of the critical failure humidity to 90% RH. This alteration, in turn, ensured the maintenance of a stable EMI SE of 27.8 dB, with a fluctuation margin of ±0.5 dB, across the 8-13 GHz range. Given the poor structural stability of MXene films in a humid environment[38], Huang et al [39] developed a higher-performance composite film by vacuum-assisted filtration, combining cellulose nanocrystals (CNC) with 2D MXenes doped with polyaniline (PANI). The conductivity was improved by optimizing the ratio of the conductive components, while the material exhibited excellent mechanical strength (158 MPa) and electromagnetic shielding effectiveness (57.1 dB) due to the strong hydrogen bonding between CNC and MXenes. Ultra-thin broadband MXene/rGO composite films (MGFs) prepared by Li et al [40]. The maximum reflection loss value of the 5-layer MGF is 57.7 dB, and the thickness is 0.148 mm; meanwhile, the effective bandwidth covers the entire measurement frequency range from 0.37 to 2.0 THz. Even more impressive is its excellent shielding performance, which reaches 54.2 dB. The measured results revealed outstanding performance in three key parameters: a peak reflection loss of 389.9 dB·mm⁻¹, a maximum electromagnetic shielding effectiveness of 366.2 dB·mm⁻¹, and an effective absorption bandwidth reaching 11.1 THz·mm⁻¹. Chang [41] et al. prepared $Ti_3C_2T_x$ thin films (Fig. 5) through a multi-interface engineering strategy. Graphene oxide (GO) and CNTs bridged adjacent and interlayer MXenes sheet layers through multiple physical and chemical interactions, respectively, resulting in lamination, and the resulting films exhibited enhanced interfacial bonding and connected conductive networks. The presence of multiple interfaces enhanced the ability of $Ti_3C_2Tx$ films to attenuate electromagnetic waves, resulting in an EMI SE of 36.19 dB and a shielding efficiency of 99.97%, meeting military requirements.

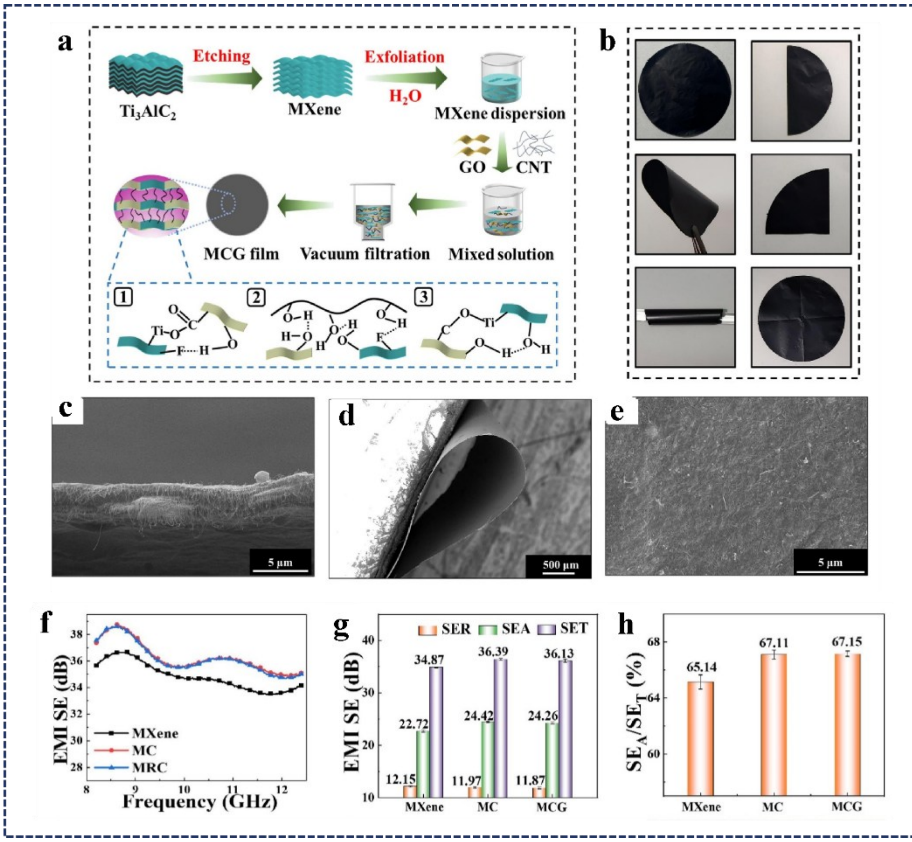



Fig. 5. (a) Schematic diagram of the fabrication of MCG film, (b) Digital photographs of the original MCG film and the MCG film after bending, folding, and rolling, the (c) cross-section, (d) bent, and (e) surface SEM images of the MCG film, (f) EMI shielding performance of the films at different frequencies, (g) $SE_A$, $SE_R$ and $SE_T$ values of the films, (h) $SE_A/SE_T$ ratios of the films[41], Copyright 2023, Elsevier Inc.

### *4.3. $Ti_3C_2T_x$ MXene-based porous materials*

The design of the porous structure helps prevent the agglomeration of the $Ti_3C_2Tx$ MXene sheets and enhances the scattering and refraction of electromagnetic waves within the material, thereby improving its electromagnetic shielding performance[42, 43]

Through the controlled directional freezing technique, Wang et al. [44] synthesized Ti3C2Tx MXene/Sodium Alginate (SA)/CNTs three-dimensional materials, constructed directionally ordered porous structures, and realized multiple reflections and scattering of incident electromagnetic waves in the phase change materials. In addition, SA has abundant hydrogen bonding, which enhances the interlayer interaction between MXene and CNTs. Under electromagnetic wave incidence perpendicular to the pore-aligned direction, the material exhibited an exceptional EMI SE of 48.0 dB in the X-band. Yang et al. [45] prepared Ti3C2Tx MXene/polyvinyl alcohol (PVA) hydrogel-like materials using an ice-template freezing and salting-out method, which exhibit high conductivity, mechanical strength, and ultra-flexibility. In addition, they feature a honeycomb-like porous structure. The thin hydrogel shows excellent electromagnetic shielding of 57 dB due to the synergistic interaction between MXene, PVA, water and the bionic porous structure. Zeng [46] et al. successfully developed a lightweight and ultra-flexible crosslinked transition metal carbide ($Ti_3C_2T_x$ MXene)-coated polyimide (PI) porous composite material (C-MXene@PI) through a chemical cross-linking method. This advanced material not only combines hydrophobicity, oxidation resistance, and extreme temperature stability, but also fully exploits MXene's intrinsic electrical conductivity. Through interfacial polarization effects between the PI matrix and the MXenes, combined with synergistic effects from the micrometer-scale porous structure of the composite foam, the material achieves integrated optimization of multifunctional characteristics. As a result, the composites exhibit excellent X-band EMI shielding (22.5 to 62.5 dB) (Fig. 6a-c). Wang et al. [14] successfully prepared a highly ordered porous composite material (PCM) by introducing magnetic Co-C@MWCNTs into the MXene matrix using directional freezing. This material demonstrates significant performance enhancement in the field of advanced EMI shielding. The Co-C@MWCNTs in the material, along with the MXene nanosheets, form a three-dimensional conductive network, which facilitates electron migration and interfacial hopping. Combined with magnetic loss mechanisms, this significantly improves electromagnetic wave absorption. The composite material exhibits excellent conductivity of 849 $S\cdot m^{-1}$ and achieves a high EMI shielding effectiveness of 41.7 dB.

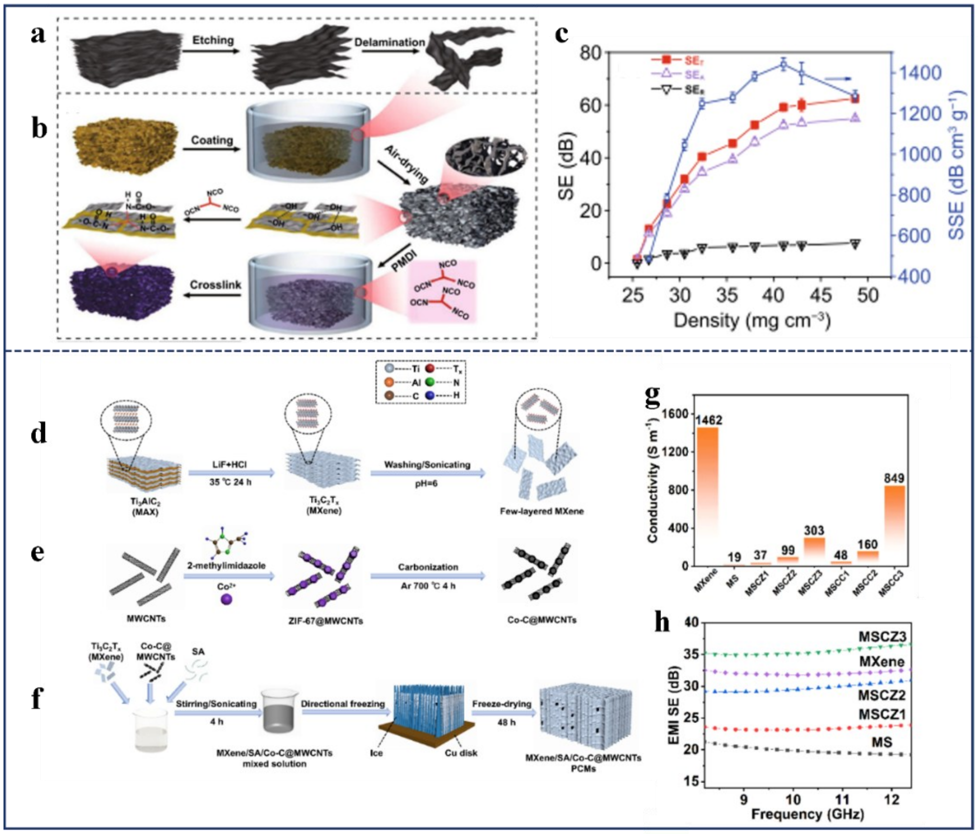



Fig. 6. Preparation method of C-MXene@PI composite foams: schematic of (a) MXene flakes and (b) C-MXene@PI composite foams, (c) EMI shielding performance (SET, SEA, and SER) and SSE of C-MXene@PI composite foams as a function of sample density [46], Copyright 2022, The Author(s), (d) Schematic of Ti3C2Tx MXene nanosheets preparation, (e) Co−C@MWCNTs, and (f) MXene/SA/Co−C@MWCNTPCM preparation process, (g) Electrical conductivity of the prepared samples, (h) EMI SE of MXene, MS, and MSCZ PCMs for parallel electromagnetic waves [14], Copyright 2024, American Chemical Society

## 5. Conclusion

This review highlights the preparation techniques for MXene nanosheets, compares the advantages and limitations of various methods, and explores their application in electromagnetic interference (EMI) shielding. The article also examines current trends in MXene research and the structural characteristics of MXene-based materials. Since the initial synthesis of MXenes, significant advancements have been made in both fabrication methods and the understanding of their structural properties. However, challenges remain in the application of MXene composites for EMI shielding, including high production costs, susceptibility to oxidative degradation, and lamellar self-stacking. Addressing these issues requires efforts to reduce production costs, develop stable antioxidants for MXenes, and design suitable structural configurations.

As a novel class of 2D transition metal carbides/nitrides, MXenes possess considerable promise for EMI shielding due to their metallic conductivity and tunable surface chemistry. With proper design and optimization, MXene-based materials are poised to make substantial contributions to various sectors, including electronics, communications, aerospace, and construction. As research progresses and technologies evolve, MXene-based EMI shielding materials are expected to have a broader range of applications and greater development potential.

## Acknowledgment

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