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REVIEW ARTICLE - MATERIALS SCIENCE (MISCELLANEOUS)

Recent Progress in MXene-Based Intelligent Electromagnetic Interference Shielding Materials

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Abstract

As the intelligent era advances at a rapid pace, the increasingly intricate electromagnetic environment is generating an urgent demand for high-performance, intelligent electromagnetic interference (EMI) shielding materials. Endowed with intrinsic high conductivity, superior hydrophilicity, abundant surface chemistry, and tailorable microstructure, MXenes serve as an ideal platform for constructing next-generation intelligent EMI shielding materials. This review elaborates on the design strategies and response mechanisms of MXene-based intelligent EMI shielding materials with different response types. It specifically clarifies the structure-activity relationship between the evolution of material microstructure and the dynamic modulation of electromagnetic parameters. It reveals the advantages and limitations of different systems through comparative analysis.

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1. Introduction

With the advent of the 5G era and the rapid development of the Internet, the number of electronic devices has surged, which has completely transformed daily life. However, the resultant complex electromagnetic radiation environment has led to an increasingly severe issue of electromagnetic pollution. Electromagnetic waves (EM) not only interfere with the normal operation of various instruments but also lead to the leakage of confidential information[1-4], and prolonged excessive exposure to EM radiation is closely associated with health risks such as cancer and leukemia[5]. Hence, developing high-performance EMI shielding materials has emerged as a key research priority.

In general, fixed compositions and structures are only capable of exhibiting one inherent EMI shielding performance. Thus, the shielding effectiveness of traditional EMI shielding materials can only be adjusted by altering their compositions and structures or replacing the original shielding materials[6-10]. Next-generation intelligent EMI shielding materials can perceive changes in the external environment (such as mechanical force, temperature, electric field, humidity, etc.) and precisely regulate EM wave reflectivity and absorptivity (R/A) by altering their internal physical/chemical states, thereby achieving reversible and tunable shielding performance[11,12].

MXenes, as a new type of layered two-dimensional conductive nanomaterial[13], have a general formula of $M_{n+1}X_nT_x$. Such materials are typically prepared via a top-down synthesis approach, specifically by selectively etching away the "A"-group metal layers from the corresponding MAX phases. Herein, M represents one or more elements from early transition metals (such as Ti, Mo, V, etc.); A denotes a group IIIA or IVA metal; X stands for carbon or nitrogen; and Tx refers to surface functional groups (such as -OH, -F, -O, -Cl, etc.) [14,15]. Compared with other nanofillers such as carbon nanotubes (CNTs), carbon nanofibers (CNFs), and graphene, MXenes stand out due to their abundant surface chemical properties and excellent electrical conductivity[16-21].For instance[22], the electromagnetic interference shielding effectiveness (EMI SE) of annealed $Ti_3C_2T_x$ and Ti_3CNT_x MXene films with a thickness of 40 μm can reach as high as 92 dB and 116 dB, respectively.

Nomenclature & Symbols			
EMI	Electromagnetic Interference	EM	Electromagnetic Waves
R/A	Reflectivity and Absorptivity Coefficient	CNTs	Carbon Nanotubes
CNFs	Carbon Nanofibers	EMI SE	Electromagnetic Interference Shielding Effectiveness
TLT	Transmission Line Theory	T	Transmission Coefficient
TPI	Trans-1,4-Polyisoprene	PEG	Polyethylene Glycol
EVA	Ethylene-Vinyl Acetate Copolymer	CF	Carbon Foam

In recent years, progress has been made in MXene-based intelligent EMI shielding materials, including those with mechanical, shape memory, phase change, and humidity responses. Under external stimulation, changes occur in the material's macroscopic and microscopic structures. These changes include variations in porosity and pore size, adjustments to the arrangement of MXene nanosheets, changes in interlayer spacing, and alterations in the continuity of conductive pathways. Meanwhile, these structural changes affect electromagnetic properties such as dielectricity and magnetism, which in turn influence the balance of impedance matching and enhance energy dissipation. Ultimately, this enables dynamic regulation of the material's electromagnetic performance.

In this review, systematically introduce the design principles, tunable mechanisms, and latest research progress of MXene-based intelligent EMI shielding materials. The focus is to reveal the evolution of the material's microstructure induced by external stimuli (stress/strain/shape memory/phase change materials) and to further explore the correlation between the dynamic reconstruction of electromagnetic parameters and the tunability of EMI SE. Finally, the challenges and prospects faced by MXene-based intelligent EMI shielding materials are also presented.

2. Mechanism of Electromagnetic Interference Shielding

Based on the transmission line theory (TLT), this model[23] treats the shielding material as a section of an ideal transmission line. When electromagnetic waves travel from free space (with characteristic impedance Z_0) toward the shielding layer, due to the mismatch between the characteristic impedance of the shielding material ($Z = \sqrt{\mu/\varepsilon}$)and Z_0, some electromagnetic waves will be reflected at the interface, while the rest will propagate into the interior of the shielding layer. Within the shielding layer, electromagnetic waves are continuously attenuated via dielectric and magnetic loss properties. Simultaneously, multiple reflections may occur at the two interfaces of the shielding layer, with the remaining electromagnetic waves ultimately penetrating the shielding layer (Fig. 1). Thus, the shielding effectiveness of the shielding material can be quantified as the superposition of three contributions, and the specific calculation is shown in Equation 1:

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

Herein, SE refers to the total shielding effectiveness, SE_R denotes the reflection coefficient, SE_A represents the absorption coefficient, and SE_M stands for multiple reflection loss (SE_M can be neglected when SE > 15 dB).

In the interaction between microwaves and materials, the ability of materials to respond to electromagnetic waves can be characterized by the reflection coefficient (R), absorption coefficient (A), and transmission coefficient (T), with these three parameters following the energy conservation relationship $R+A+T=1$[4,24,25]. These parameters can be indirectly obtained via scattering parameters (S-parameters). Specifically, the reflected and transmitted energy power of microwaves are described by S_{11} (S_{22}) and S_{21} (S_{12}) in S-parameters, with their relationships given as follows:

$$R=|S_{11}|^2=|S_{22}|^2 \tag{2}$$

$$T=|S_{21}|^2=|S_{12}|^2 \tag{3}$$

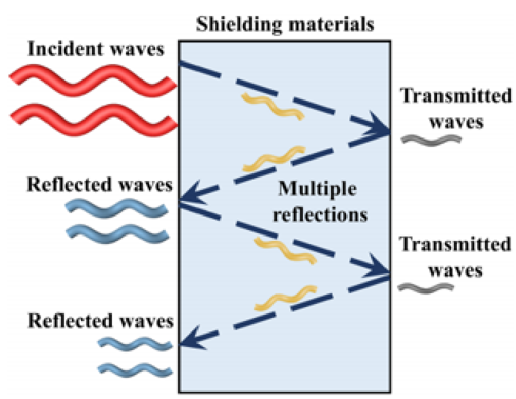

Fig. 1. The shielding mechanism of shielding materials[26]

3. MXene-Based Intelligent Electromagnetic Shielding Materials

3.1. Mechanically responsive electromagnetic interference shielding materials

Strain-responsive EMI shielding materials represent an innovative approach to developing dynamic, tunable shielding systems. Such materials typically consist of an elastic polymer matrix embedded with conductive or magnetic fillers[27] ,which can respond to mechanical deformations (e.g., compressive or tensile strain). When strain is applied, the arrangement and spacing of fillers alter, triggering changes in the material's electromagnetic properties, including its electrical conductivity, magnetic permeability, and dielectric constant[28]. Such mechanical deformation can either enhance or diminish the material's capacity to block electromagnetic waves, thereby enabling real-time modulation of SE.Strain-responsive EMI shielding materials hold particular promise for applications requiring flexible and adaptive shielding, such as wearable electronic devices[29], soft robotics, or aerospace systems. Sponges, foams, and aerogels are common materials employed for EMI shielding. Their porous structures can significantly enhance multiple microwave reflections and scattering, thereby contributing to the absorption mechanism[30,31]. For instance, Yuan et al. [32] fabricated MXene/melamine sponges with reversible compressibility and 3D printed resin matrix composites (3DMMS) via dip-coating and freeze-drying processes. In these composites, melamine sponges serve as lightweight porous frameworks, and their surfaces are coated with MXene nanosheets to form a three-dimensional MXene network. The presence of MXene nanosheets, on one hand, enhances the skeletal support by increasing the volume fraction, thereby improving the mechanical properties of the polymer. This further endows the 3DMMS sponge with excellent shielding performance, accompanied by an absorption-dominated loss mechanism. The shielding performance of 3DMMS sponges can be regulated via mechanical compression. As shown in Fig. 2a, with the increase of applied compressive strain, the absorption-dominated SE in the S-band (2.6–3.95 GHz) can be freely adjusted from 0 dB to 43.1 dB. Meanwhile, under the regulation of compressive strain, the electrical conductivities of samples containing different concentrations of MXene all show an upward trend with increasing strain: the electrical conductivity of MMS-1 increases from 18.2 S/m to 136.8 S/m, that of MMS-2 from 54 S/m to 130 S/m, and that of MMS-3 from 56 S/m to 136.8 S/m. They attribute the increase in SE primarily to changes in contact area, porosity, and pore size during compression, which in turn induce variations in electrical conductivity, impedance matching, as well as multiple reflections and scattering within the porous structure.

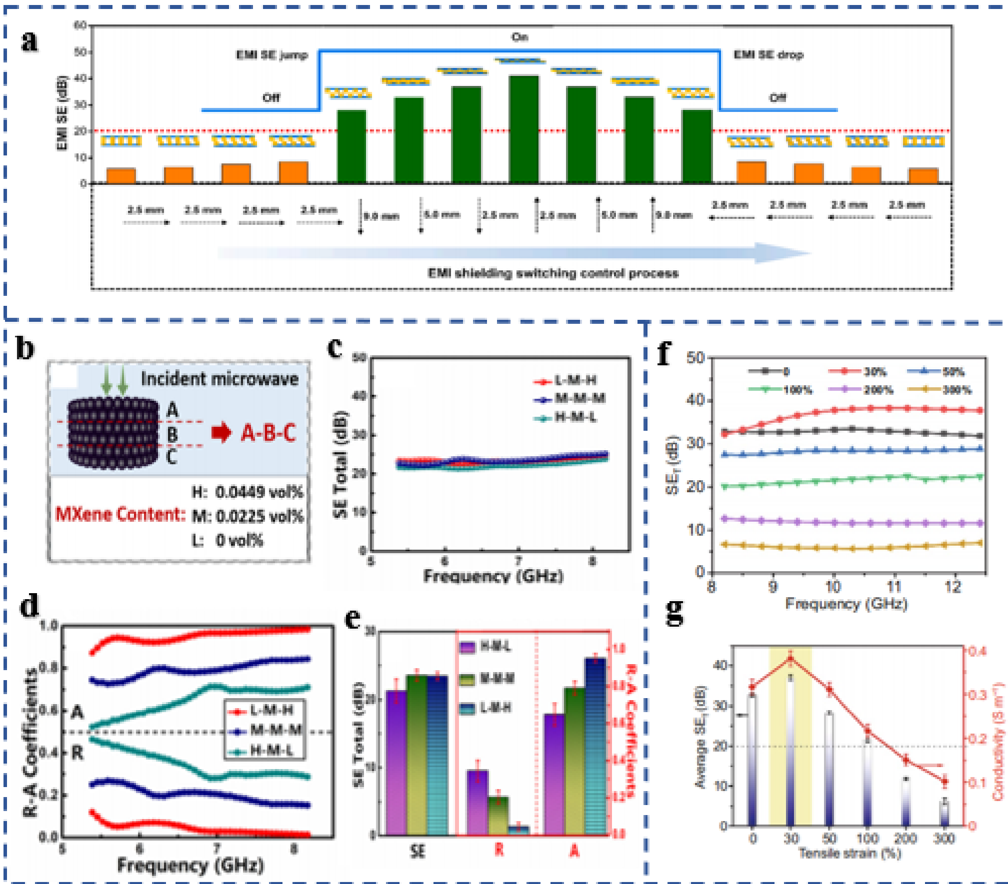

Fig. 2. (a) An integrated EMI shielding switch control process of 3DMMS, Copyright 2021 Elsevier Ltd. [32], (b) Schemes of PDMS/MPFB composite foams with asymmetric MXene networks, (c) SE Total, (d-e) R-A coefficients of H (High MXene content layer, ~0.0449 vol% MXene)-M (Medium MXene content layer, ~0.0225 vol% MXene)-L (Low MXene content layer, 0 vol% MXene), M-M-M and L-M-H samples (~12 mm in thickness), Copyright 2020 Elsevier Ltd. [33], (f) SE_T curves of MXene organohydrogel with different tensile strains, (g) Variations of average SE_T value and conductivity of MXene organohydrogel with tensile strain [34]

Electrical conductivity is a key factor affecting the final EMI shielding performance [35]. An increase in electrical conductivity always leads to impedance mismatch, which in turn results in increased reflection of electromagnetic waves by the material [36]. Therefore, it is necessary to carefully design the filler matrix and its response to strain to mitigate the loss of SE_A and ensure that the material still meets the required performance. As noted by Jia et al. [33] in their research on compressible polymer/MXene composite foam beads, they used polyaniline (PANI) as an auxiliary material to prepare MXene-decorated polymer foam beads (MPFBs) as the substrate, which were finally encapsulated with polydimethylsiloxane (PDMS). This design enabled the SE to decrease from ~27.7 dB at 0% strain to ~16.2 dB at 40% strain as the compressive strain changed. Meanwhile, through the design of an asymmetric gradient structure (Fig. 2b), although the SE value did not change significantly (Fig. 2c), the impedance matching was optimized, and the electromagnetic wave reflection at the interface was significantly reduced (Fig. 2d, e). This allowed more electromagnetic waves to penetrate the composite material, which were then sufficiently attenuated by the conductive network—perfected as conductivity increased—through conduction loss, polarization loss, and multiple reflections/scattering. Ultimately, this achieved the effect of maintaining satisfactory SE while exhibiting an extremely low reflection coefficient (R) and high absorption coefficient

(A) [37]. In addition, tensile strain is also a common means to regulate SE. Stretching or releasing the material can alter its electrical conductivity, thereby leading to a decrease in its EMI shielding effectiveness [38,39]. Conductive hydrogels, as a common structure for EMI shielding materials, are widely used in the field of electromagnetic protection for flexible electronics and wearable devices, thanks to their excellent flexibility, stretchability, and good compatibility with conductive fillers such as MXene. For example, Yu et al. [34] proposed a new type of MXene organic hydrogel with excellent EMI shielding performance.They constructed a conductive network using MXene, with a water/glycerol binary solvent serving as an ion transport channel. This hydrogel exhibits non-monotonic changes in SE as tensile strain increases from 0% to 300% (Fig. 2f): at a small tensile strain of 30%, SE increases from the initial 32.8 dB to 37 dB; conversely, it gradually decreases with further increases in strain. The authors attribute this phenomenon to changes in the arrangement of MXene nanosheets and pore spacing during stretching, which further affect electron conduction paths and the ion affinity of pores, thereby enabling the switching on and off of EMI shielding.

3.2. Shape memory-responsive EMI shielding materials

Shape memory responsive intelligent EMI shielding materials, leveraging the self-fixation property of shape memory polymers (SMPs) [40], effectively overcome the limitation of traditional strain-responsive materials that struggle to stably maintain specific SE without external force. Moreover, they can recover their original shape and shielding performance under specific conditions, enabling dynamic regulation with "self-fixation and recoverability". Incorporating SMPs into EMI shielding materials provides an innovative approach to developing new materials with both high EMI shielding performance and intelligent regulation capabilities. For example, Jia et al.[40] Fabricated TPI-M/CF composites by coating a trans-1,4-polyisoprene (TPI)-MXene layer on the framework of compressible wood-derived carbon foam (CF). Herein, TPI, as a typical SMP, can be easily compressed and deformed in an environment above its melting temperature. After cooling, the deformation can be quickly fixed through crystalline domains (Fig. 3a), enabling stable maintenance of the temporary shape without external force. When subjected to heating or electrical stimulation, the material returns to its original state by virtue of the entropy elasticity of the TPI cross-linked network and the inherent elasticity of the CF framework, with the corresponding SE value also bouncing back (Fig. 3b). In detail, during the recovery phase, the total shielding effectiveness is nearly recoverable to its initial level: the value reaches roughly 27.4 dB when the strain bounces back to around 30%, and climbs further to about 35.6 dB once the material regains its original thickness. This fully illustrates that the self-fixation capability of the material enables the controllable adjustment of its shielding performance.

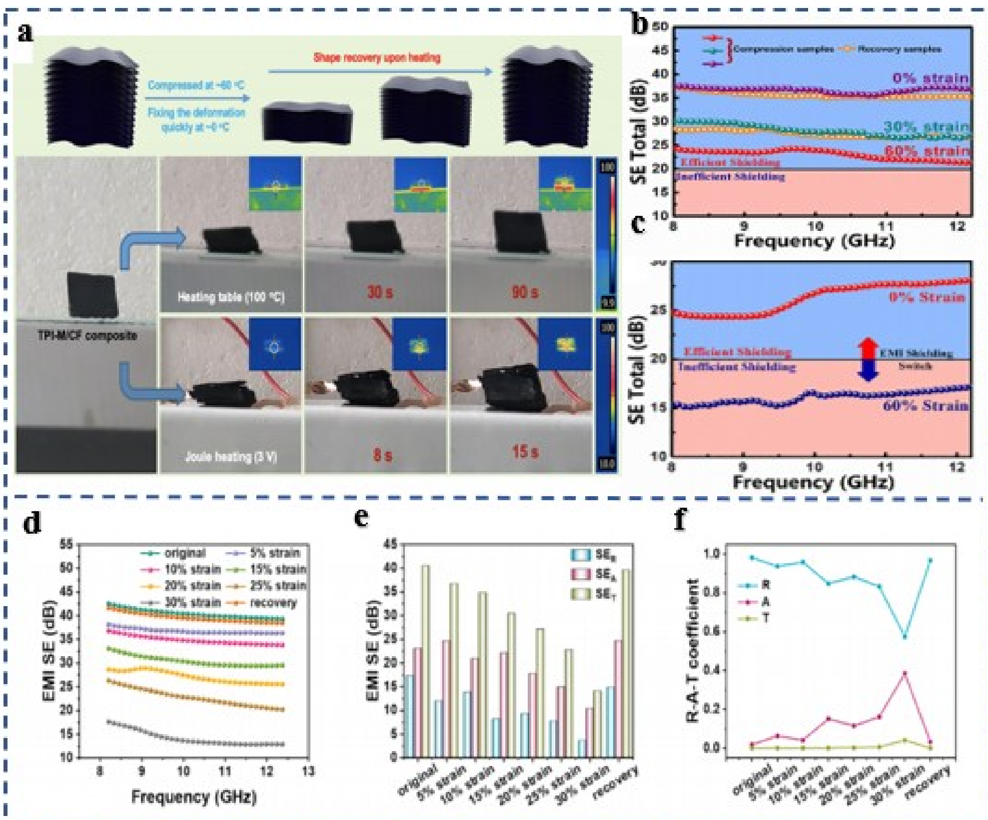

Fig. 3. (a) Photographs and corresponding infrared thermal images showing the thermally and electrically stimulated shape-memory behaviors of TPI-M/CF composite with 10 wt% CTAB-MXene loading, (b) SE Total of TPI-M/CF composite (~5 wt% CTAB-MXene) with different compressive strains, exhibiting function-switchable EMI-shielding behavior, (c) SE Total of TPI-M/CF composite (~10 wt% CTAB-MXene) during the compression-recovery process with different compressive strains, exhibiting function-tunable EMI-shielding behavior, Copyright 2020 Elsevier B.V. [40], (d-f) EMI SE, SE_R, SE_A, SE_T and R-A-T coefficient of EVA/MXene/EVA-40 composite membrane under different tensile strains, Copyright 2024 Elsevier B.V. [41]

He et al. [42] reported a multifunctional phase-change melamine foam composite (MF@MA/PEG) that utilizes light/heat-responsive shape memory properties. Polyethylene glycol (PEG) is encapsulated in MXene/silver nanowire (AgNW)-modified composite foam via vacuum impregnation. The material undergoes thickness changes under light or heat stimulation, and self-fixes this state by virtue of the shape memory effect, thereby regulating electrical conductivity and EMI SE through thickness adjustment. In addition, the integration of shape memory polymers endows materials with more excellent performance. Zeng et al. [41] combined MXene with ethylene-vinyl acetate copolymer (EVA) to prepare EVA/MXene/EVA composite films. Relying on the shape memory capability of EVA, the composite film can maintain a temporary shape when the tensile strain increases to 30%, resulting in a decrease in SE from 40.5 dB to 14.1 dB. During shape recovery, the defects in the conductive paths are reconnected to form a complete network, and the SE value rebounds. Moreover, the material retains stable shielding performance even after 500 cycles of bending, folding, and exposure to acid-base environments. Its excellent stability is attributed to the flexibility and corrosion resistance of EVA.

3.3. Phase change material-responsive EMI shielding materials

Introducing phase change materials (PCMs) into EMI shielding materials also offers a novel strategy for intelligent EMI shielding materials. PCMs are capable of undergoing phase transitions at specific temperatures, thus dynamically adjusting the electromagnetic properties of the materials [43-45]. For example, Fang et al. [46] integrated paraffin-nanoclay/MXene core-shell microspheres into hydrogels via in-situ polymerization, constructing a microcapacitor network structure and successfully achieving EMI shielding performance tunable by temperature and tensile strain. Due to the solid-liquid phase transition, the SE of the organic hydrogel at room temperature (Fig. 4a) decreases monotonically with increasing tensile strain, while at high temperature (Fig. 4b) it first increases and then decreases. It maintains effective shielding even under large strain, exhibiting significantly different strain-responsive EMI shielding performance. The authors attribute such differences mainly to variations in microstructure, particularly the shape and distribution of microspheres. This characteristic provides a new approach for realizing multiple modes of shielding performance regulation.

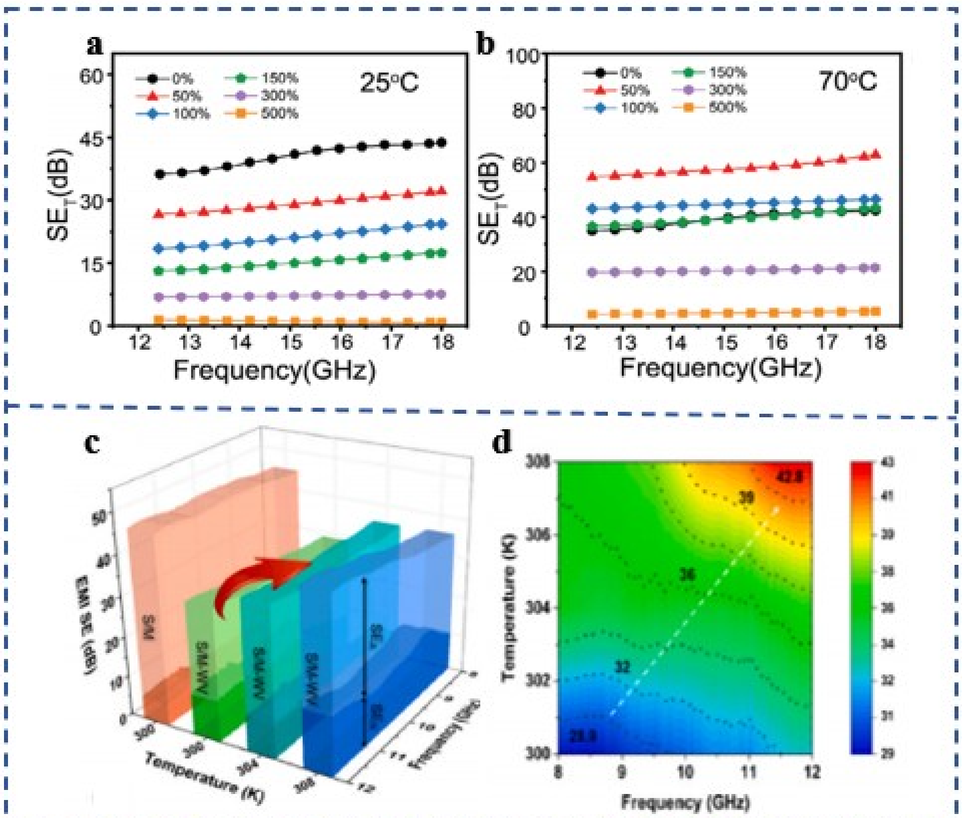

Fig. 4. (a) SE curves of M-organohydrogel-2:2 under different tensile strains in the Ku(12-18GHz) band measured at 25 °C, (b) SE curves of M-organohydrogel-2:2, Copyright 2024 Wiley-VCH GmbH. [46], (c) 3D plot of SE_A and SE_R versus temperature and frequency at a thickness of 2 mm, (d) 3D plot of EMI SE versus temperature and frequency, Copyright 2023 Elsevier Ltd. [47]

In addition, dynamic regulation of EMI shielding effectiveness can also be achieved based on macroscopic deformation of shielding materials. Vanadium dioxide (VO_2) exhibits unique phase transition properties: its phase transition temperature is relatively mild (<68 °C), and the conversion from insulating phase to metallic phase is rapidly reversible. Such distinctive reversibility, along with drastic changes in electrical conductivity and dielectric constant, endows it with potential application value in the field of intelligent EMI shielding. As a case in point, the intelligently tunable shielding composite developed by Qian et al. [47] is capable of converting absorbed electromagnetic energy into thermal energy via the synergistic interaction between $Ti_3C_2T_x$ and tungsten-doped VO_2 (WVO_2). This thermal energy triggers a phase transition in WVO_2 [48], which in turn enhances the material's EMI shielding efficacy. When the temperature increases from 300 K to 308 K, the composite's EMI shielding performance is notably improved, with SE rising from 28.9 dB to 42.8 dB (Fig. 4d, e), thus achieving dynamic adjustability of shielding performance.

3.4. Acid-base and humidity-responsive EMI shielding materials

Acid-base responsive systems have been effectively applied in the field of EMI shielding. For example, Li et al. [49] fabricated conductive polyaniline (PANI)/MXene/cotton fabric (PMCFs) composites via vacuum filtration-assisted spray coating. Owing to the impact of PANI on the interlayer conductive pathways of MXene, the material exhibits unique acid-base responsive properties (Fig. 5a). Under alternating stimulation with hydrogen chloride and ammonia vapors (Fig. 5b, c), it can adaptively switch between effective strong shielding (24 dB) and ineffective weak shielding (15 dB) states, acting as a "switch" for electromagnetic shielding. This characteristic endows the multifunctional fabric with great application potential in intelligent clothing and intelligent EMI shielding response scenarios in special chemical environments.

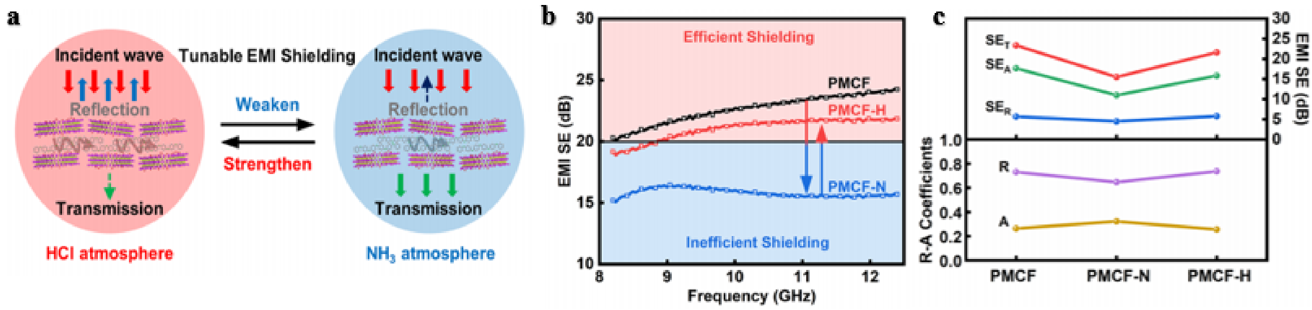

Fig. 5. (a) Schematic illustrating the mechanisms of acid/alkali-responsive and tunable EMI shielding behaviors, (b) EMI SE, and (c) SE_A, SE_T, SE_R, and R-A coefficients of PMCF, PMCF-N, and PMCF-H, Copyright , 2022, American Chemical Society. [49]

In addition, humidity-responsive EMI shielding materials primarily regulate the EMI shielding effectiveness of composites by altering the interlayer polarization and energy loss of materials through changes in water content [50]. For instance, Wei et al. [51] prepared MXene/polyvinyl alcohol (PVA) hydrogels via a freeze-salting-out method. Water, as the core component, fills the porous structure, and its high dielectric properties can enhance polarization loss, enabling the hydrogel to achieve an SE of 53.9 dB in the hydrogel state. After freeze-drying, the SE decreases to 11.5 dB accordingly. Mei et al. [52] prepared MXene/polyacrylic acid (PAA)-chitosan (CS) hydrogels using a double-network strategy combined with the Hofmeister effect, while further strengthening and toughening the gel with $(NH_4)_2SO_4$ solution. A high shielding effectiveness of 73.8 dB was achieved in the terahertz band. However, after long-term dehydration, the SE dropped significantly to 36.4 dB due to reduced polarization loss caused by decreased moisture. Notably, the material remained stable in performance after repeated stretching and dehydration. Despite progress in water-responsive materials, precise control over moisture stimulation in atmospheric environments remains difficult, posing challenges to their practical applications.

3.5. Others

In the research on responsive and adaptive intelligent EMI shielding materials, besides the aforementioned response types, there are various novel response mechanisms worthy of attention. For example, electromagnetic interference shielding effectiveness can be regulated by electrochemical stimulation. Han et al. [53] realized the intelligent regulation of EMI shielding effectiveness through electrochemically modulated MXene films. Due to the layered structure and electrochemical response characteristics of MXene, the interlayer spacing changes under the action of ion intercalation and deintercalation, enabling reversible regulation of EMI shielding effectiveness. For instance, the EMI shielding effectiveness of V_2CT_x in H_2SO_4 can decrease from 24.3 dB to 18.1 dB. Meanwhile, $Ti_3C_2T_x$ can be transformed from a strong shielding state to a wave-transparent state through electrochemical oxidation, which provides a typical case for electrochemically regulated intelligent shielding. In addition, adjusting the shielding performance can also be effectively achieved by altering the angle between the material and the propagation direction of the incident wave's electric field. Jiang et al. [54] fabricated multifunctional MXene gratings via ink direct-writing 3D printing. By regulating the crossing angle between the grating wires and the electric field of incident electromagnetic waves, they realized highly reversible switching between shielding "on" (28.0 dB) and "off" (0.5 dB) states, with wide-range adjustment capability and high flexibility. Wei et al. [55], on the other hand, coated MXene on the surface of natural wood to prepare highly anisotropic MXene@wood composites. Their tangential cross-sections exhibit better impedance matching due to the porous structure and free radical properties. By changing the dihedral angle between the wood grain and the electromagnetic wave's electric field, the shielding effectiveness can be rapidly increased from 27.4 dB (90°) to 57.6 dB (0°), achieving a significant adjustment.

4. Conclusion

This paper summarizes recent progress in EMI shielding materials with different response types. These materials can be categorized according to the stimulus type as mechanically-responsive, shape memory-responsive, phase change material-responsive, acid-base responsive, or humidity-responsive. However, developing MXene-based intelligent EMI shielding materials faces many challenges. The stability of MXene is the key bottleneck because MXene is prone to oxidative degradation, which destroys conductive networks and attenuates shielding performance. Long-term stability must be improved. Additionally, multifunctional materials integrate the advantages of different responsive materials and can respond to two or more external stimuli. They can also be reversibly switched between different efficacies. However, existing systems mostly rely on single-stimulus responses, which makes it difficult to accurately regulate complex environments. The ability to regulate multiple responses synergistically is insufficient. Therefore, smart electromagnetic shielding materials with multi-stimulus responses present both challenges and opportunities.

Acknowledgment

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References

[1] D. Dai, Z. Wang, and J. E. J. O. L. Bowers, “Ultrashort broadband polarization -beam splitter based on an asymmetrical directional coupler,” Advanced Materials, vol. 36, no. 13, pp. 2590-2592, 2011, http://dx.doi.org/10.1002/adma.202202982.
[2] C. Maosheng, W. Xixi, C. Wenqiang, F. Xiaoyong, W. Bo, and Y. J. S. Jie, “Thermally Driven Transport and Relaxation Switching Self-Powered Electromagnetic Energy Conversion,” Small, pp. 1800987-, 2018, http://dx.doi.org/10.1002/smll.201800987.
[3] O. Pitkänen, J. Tolvanen, I. Szenti, A. k. Kukovecz, J. Hannu, H. Jantunen, K. J. A. A. M. Kordas, and Interfaces, “Lightweight hierarchical carbon nanocomposites with highly efficient and tunable electromagnetic interference shielding properties,” ACS Applied Materials & Interfaces, vol. 11, no. 21, pp. 19331-19338, 2019, http://dx.doi.org/10.1021/acsami.9b21048.
[4] D. X. Yan, H. Pang, B. Li, R. Vajtai, L. Xu, P. G. Ren, J. H. Wang, and Z. M. J. A. F. M. Li, “Structured reduced graphene oxide/polymer composites for ultra-efficient electromagnetic interference shielding,” Advanced Functional Materials, vol. 25, no. 4, pp. 559-566, 2015, http://dx.doi.org/10.1002/adfm.201403809.
[5] X. Zhou, P. Min, Y. Liu, M. Jin, Z.-Z. Yu, and H.-B. J. S. Zhang, “Insulating electromagnetic-shielding silicone compound enables direct potting electronics,” Science, vol. 385, no. 6714, pp. 1205-1210, 2024, http://dx.doi.org/10.1126/science.adp6581.
[6] S. M. Zachariah, Y. Grohens, N. Kalarikkal, and S. J. P. C. Thomas, “Hybrid materials for electromagnetic shielding: A review,” Polymer Composites, vol. 43, no. 5, pp. 2507-2544, 2022, http://dx.doi.org/10.1002/pc.26595.
[7] Y. Yang, C.-L. Luo, X.-D. Chen, M. J. C. S. Wang, and Technology, “Sustainable electromagnetic shielding graphene/nanocellulose thin films with excellent joule heating and mechanical properties via in-situ mechanical exfoliation and crosslinking with cations,” Composites Science and Technology, vol. 233, pp. 109913, 2023, http://dx.doi.org/10.1016/j.compscitech.2023.109913.
[8] Y. Wang, Y.-N. Gao, T.-N. Yue, X.-D. Chen, and M. J. A. S. S. Wang, “Achieving high-performance and tunable microwave shielding in multi-walled carbon nanotubes/polydimethylsiloxane composites containing liquid metals,” Composites Part B: Engineering, vol. 563, pp. 150255, 2021, http://dx.doi.org/10.1016/j.compositesb.2022.110402.
[9] J.-R. Tao, C.-L. Luo, M.-L. Huang, Y.-X. Weng, M. J. C. P. A. A. S. Wang, and Manufacturing, “Construction of unique conductive networks in carbon nanotubes/polymer composites via poly (ε-caprolactone) inducing partial aggregation of carbon nanotubes for microwave shielding enhancement,” Composites Part A: Applied Science and Manufacturing, vol. 164, pp. 107304, 2023, http://dx.doi.org/10.1016/j.compositesa.2022.107304.
[10] Q. M. He, J. R. Tao, and D. J. C. e. j. Yang, “Surface wrinkles enhancing electromagnetic interference shielding of copper coated poly dime thy lsiloxane: A simulation and experimental study,” Chemical Engineering Journal, 2023, http://dx.doi.org/10.1016/j.cej.2022.140162.
[11] S. Verma, M. Dhangar, S. Paul, K. Chaturvedi, M. A. Khan, and A. K. J. E. M. L. Srivastava, “Recent advances for fabricating smart electromagnetic interference shielding textile: a comprehensive review,” Electronic Materials Letters, vol. 18, no. 4, pp. 331-344, 2022, http://dx.doi.org/10.1007/s13391-022-00344-w.
[12] Y. Xia, W. Gao, and C. J. A. F. M. Gao, “A review on graphene-based electromagnetic functional materials: electromagnetic wave shielding and absorption,” Advanced Functional Materials, vol. 32, no. 42, pp. 2204591, 2022, http://dx.doi.org/10.1002/adfm.202204591.
[13] M. Naguib, O. Mashtalir, J. Carle, V. Presser, J. Lu, L. Hultman, Y. Gogotsi, and M. W. J. A. n. Barsoum, “Two-dimensional transition metal carbides,” ACS Nano, vol. 6, no. 2, pp. 1322-1331, 2012, http://dx.doi.org/10.1021/nn204153h.
[14] B. Anasori, M. R. Lukatskaya, and Y. Gogotsi, "2D metal carbides and nitrides (MXenes) for energy storage," Nature Reviews Materials, pp. 677-722: Jenny Stanford Publishing, 2023.
[15] M. Naguib, V. N. Mochalin, M. W. Barsoum, and Y. J. A. m. Gogotsi, “25th anniversary article: MXenes: a new family of two-dimensional materials,” Advanced Materials, vol. 26, no. 7, pp. 992-1005, 2014, http://dx.doi.org/10.1002/adma.201304138.
[16] C. Caloz, and T. Itoh, Electromagnetic metamaterials: transmission line theory and microwave applications, : John Wiley & Sons, 2005.
[17] Z. Fan, D. Wang, Y. Yuan, Y. Wang, and Z. J. C. E. J. Xie, “A lightweight and conductive MXene/graphene hybrid foam for superior electromagnetic interference shielding,” Chemical Engineering Journal, vol. 381, pp. 122696, 2019, http://dx.doi.org/10.1016/j.cej.2019.122696.
[18] X. Jia, B. Shen, L. Zhang, and W. J. C. P. B. E. Zheng, “Waterproof MXene-decorated wood-pulp fabrics for high-efficiency electromagnetic interference shielding and Joule heating,” Composites Part B: Engineering, vol. 198, pp. 108250, 2020, http://dx.doi.org/10.1016/j.compositesb.2020.108250.
[19] X. Li, X. Yin, M. Han, C. Song, X. Sun, H. Xu, L. Cheng, and L. J. J. m. c. c. Zhang, “A controllable heterogeneous structure and electromagnetic wave absorption properties of Ti2CTx MXene,” Journal of Materials Chemistry C, pp. 10.1039.C7TC01991B, 2017, http://dx.doi.org/doi.org/10.1039/c7tc01991b.
[20] J. Luo, S. Gao, H. Luo, L. Wang, X. Huang, Z. Guo, X. Lai, L. Lin, R. K. Li, and J. J. C. E. J. Gao, “Superhydrophobic and breathable smart MXene-based textile for multifunctional wearable sensing electronics,” Chemical Engineering Journal, vol. 406, pp. 126898, 2021, http://dx.doi.org/10.1016/j.cej.2020.126898.
[21] H. Shi, M. Yue, C. J. Zhang, Y. Dong, P. Lu, S. Zheng, H. Huang, J. Chen, P. Wen, and Z. J. ACS N. Xu, “3D Flexible, Conductive, and Recyclable Ti3C2Tx MXene-Melamine Foam for High-Areal-Capacity and Long-Lifetime Alkali-Metal Anode,” ACS Nano, vol. 14, no. 7, pp. 11, 2020, http://dx.doi.org/10.1021/acsnano.0c03042.
[22] Iqbal, Aamir, Faisal Shahzad, Kanit Hantanasirisakul, Myung-Ki Kim, Jisung Kwon, Junpyo Hong, Hyerim Kim, Daesin Kim, Yury Gogotsi, and Chong Min Koo. "Anomalous absorption of electromagnetic waves by 2D transition metal carbonitride Ti3CNT x (MXene)." Science 369, no. 6502, 446-450, 2020, https://doi.org/10.1126/science.aba7977.
[23] C. Caloz, and T. J. I. M. S. I. m. S. d. p. P. Itoh, “Novel microwave devices and structures based on the transmission line approach of meta-materials,” Science, 2003, http://dx.doi.org/10.1126/science.aba7977.

[24] S. Geetha, K. K. S. Kumar, C. R. K. Rao, M. Vijayan, and D. C. J. J. o. A. P. S. Trivedi, “EMI shielding: Methods and materials—A review,” Journal of Applied Polymer Science, vol. 112, no. 4, pp. 2073-2086, 2010, http://dx.doi.org/10.1002/app.29812.

[25] A. A. Isari, A. Ghaffarkhah, S. A. Hashemi, S. Wuttke, and M. J. A. M. Arjmand, “Structural design for EMI shielding: from underlying mechanisms to common pitfalls,” Advanced Materials, vol. 36, no. 24, pp. 2310683, 2024, http://dx.doi.org/10.1002/adma.202310683.

[26] W. Lei, C. Jiawei, Z. Y. W. Y. Y. H. D. X. J. A. composites, and h. materials, “Current advances and future perspectives of MXene-based electromagnetic interference shielding materials,” vol. 6, no. 5, 2023

[27] Y. Wang, Y. N. Gao, T. N. Yue, X. D. Chen, and M. J. A. S. S. Wang, “Achieving high-performance and tunable microwave shielding inmulti-walled carbon nanotubes/polydimethylsiloxane composites containing liquid metals,” Applied Surface Science, vol. 563, no. Octa15, pp. 150255.1-150255.11, 2021, http://dx.doi.org/10.1016/j.apsusc.2021.150255.

[28] Y. Shi, S. Xu, J. Du, and J. J. M. T. P. Qiu, “Strain-responsive 3D hierarchical composites for smart microwave absorption modulation within broad C-Ku band,” Materials Today Physics, vol. 27, 2022, http://dx.doi.org/10.1016/j.mtphys.2022.100823.

[29] T. Someya, Z. Bao, and G. G. J. N. Malliaras, “The rise of plastic bioelectronics,” Nature, vol. 540, no. 7633, pp. 379-385, 2016, http://dx.doi.org/10.1038/nature21004.

[30] Y.-Y. Wang, Z.-H. Zhou, C.-G. Zhou, W.-J. Sun, J.-F. Gao, K. Dai, D.-X. Yan, Z.-M. J. A. a. m. Li, and interfaces, “Lightweight and robust carbon nanotube/polyimide foam for efficient and heat-resistant electromagnetic interference shielding and microwave absorption,” ACS Applied Materials & Interfaces, vol. 12, no. 7, pp. 8704-8712, 2020, http://dx.doi.org/10.1021/acsami.9b21048.

[31] C. Weng, G. Wang, Z. Dai, Y. Pei, L. Liu, and Z. J. N. Zhang, “Buckled AgNW/MXene hybrid hierarchical sponges for high-performance electromagnetic interference shielding,” Nanoscale, vol. 11, no. 47, pp. 22804-22812, 2019, http://dx.doi.org/10.1039/c9nr07988b.

[32] W. Yuan, H. Liu, X. Wang, L. Huang, F. Yin, Y. J. C. P. A. A. S. Yuan, and Manufacturing, “Conductive MXene/melamine sponge combined with 3D printing resin base prepared as an electromagnetic interferences shielding switch,” Composites Part A: Applied Science and Manufacturing, vol. 143, pp. 106238, 2021, http://dx.doi.org/10.1016/j.compositesa.2020.106238.

[33] X. Jia, B. Shen, L. Zhang, and W. J. C. Zheng, “Construction of compressible Polymer/MXene composite foams for high-performance absorption-dominated electromagnetic shielding with ultra-low reflectivity,” Carbon, vol. 176, pp. 660-661, 2021, http://dx.doi.org/10.1016/j.carbon.2020.11.036.

[34] Y. Yu, P. Yi, W. Xu, X. Sun, G. Deng, X. Liu, J. Shui, and R. J. N.-M. L. Yu, “Environmentally Tough and Stretchable MXene Organohydrogel with Exceptionally Enhanced Electromagnetic Interference Shielding Performances,” 2022, http://dx.doi.org/10.1007/s40820-022-00819-3.

[35] H. Abbasi, M. Antunes, and J. I. J. P. i. M. S. Velasco, “Recent advances in carbon-based polymer nanocomposites for electromagnetic interference shielding,” Progress in Materials Science, vol. 103, pp. 319-373, 2019, http://dx.doi.org/10.1016/j.pmatsci.2019.02.003.

[36] J. Ma, M. Zhan, K. J. A. A. M. Wang, and Interfaces, “Ultralightweight silver nanowires hybrid polyimide composite foams for high-performance electromagnetic interference shielding,” ACS Applied Materials & Interfaces, vol. 7, no. 1, pp. 563-76, 2015, http://dx.doi.org/10.1021/am5067095.

[37] A. Sheng, W. Ren, Y. Yang, D.-X. Yan, H. Duan, G. Zhao, Y. Liu, Z.-M. J. C. P. A. A. S. Li, and Manufacturing, “Multilayer WPU conductive composites with controllable electro-magnetic gradient for absorption-dominated electromagnetic interference shielding,” Composites Part A: Applied Science and Manufacturing, vol. 129, pp. 105692, 2020, http://dx.doi.org/10.1016/j.compositesa.2019.105692.

[38] H. Sun, Y. Zhao, S. Jiao, C. Wang, Y. Jia, K. Dai, G. Zheng, C. Liu, P. Wan, and C. J. A. F. M. Shen, “Environment tolerant conductive nanocomposite organohydrogels as flexible strain sensors and power sources for sustainable electronics,” Advanced Functional Materials, vol. 31, no. 24, pp. 2101696, 2021, http://dx.doi.org/10.1002/adfm.202101696.

[39] Y. Niu, H. Liu, R. He, M. Luo, M. Shu, and F. J. S. Xu, “Environmentally Compatible Wearable Electronics Based on Ionically Conductive Organohydrogels for Health Monitoring with Thermal Compatibility, Anti-Dehydration, and Underwater Adhesion,” Small, vol. 17, no. 24, pp. 2101151, 2021, http://dx.doi.org/10.1002/smll.202101151.

[40] X. Jia, B. Shen, L. Zhang, and W. J. C. E. J. Zheng, “Construction of shape-memory carbon foam composites for adjustable EMI shielding under self-fixable mechanical deformation,” Chemical Engineering Journal, vol. 405, pp. 126927, 2021, http://dx.doi.org/10.1016/j.cej.2020.126927.

[41] Zeng, Zhiyong, Jv Li, Leimei Fang, Chuanru Zheng, Hongmei Chen, Jian Huang, Kun Qian, Haoxuan Li, and Wenbing Li. "Flexible and durable shape memory EVA/MXene/EVA fiber membrane for programmable EMI shielding." Chemical Engineering Journal 501, 157599, 2024, http://dx.doi.org/10.1016/j.cej.2024.157599.

[42] Y. J. He, Y. W. Shao, Y. Y. J. A. a. m. Xiao, and interfaces, “Multifunctional Phase Change Composites Based on Elastic MXene/Silver Nanowire Sponges for Excellent Thermal/Solar/Electric Energy Storage, Shape Memory, and Adjustable Electromagnetic Interference Shielding Functions,” ACS Applied Materials & Interfaces, no. 4, pp. 14, 2022, http://dx.doi.org/10.1021/acsami.1c23303.

[43] A. V. Menon, G. Madras, and S. J. C. E. J. Bose, “Shape memory polyurethane nanocomposites with porous architectures for enhanced microwave shielding,” Chemical Engineering Journal, vol. 352, pp. 590-600, 2018, http://dx.doi.org/10.1016/j.cej.2018.07.048.

[44] Y. Yan, H. Xia, Y. Qiu, Z. Xu, and Q. Q. J. R. A. Ni, “Fabrication of gradient vapor grown carbon fiber based polyurethane foam for shape memory driven microwave shielding,” RSC Advances, vol. 9, 2019, http://dx.doi.org/10.1039/C9RA00028C.

[45] H. Lu, Z. Li, X. Qi, L. Xu, Z. Chi, D. Duan, M. Z. Islam, W. Wang, X. Jin, Y. J. C. S. Zhu, and Technology, “Flexible, electrothermal-driven controllable carbon fiber/poly (ethylene-co-vinyl acetate) shape memory composites for electromagnetic shielding,” Composites Science and Technology, vol. 207, pp. 108697, 2021, http://dx.doi.org/10.1016/j.compscitech.2021.108697.

[46] M. Fang, L. Huang, Z. Cui, P. Yi, H. Zou, X. Li, G. Deng, C. Chen, Z. Geng, and J. J. A. F. M. He, “Phase-Transition Microcapacitor Network in Organohydrogel for Absorption-Dominated Electromagnetic Interference Shielding and Multi-Mode Intelligent Responsiveness,” vol. 35, no. 18, 2025.

[47] H. Qian, W. Jiang, X. Shi, Q. Cao, B. Jiang, and Y. J. C. Huang, “Pushing electromagnetic interference shielding self-enhanced based on smart Ti3C2Tx-WVO2 thermal management composite,” Carbon, vol. 210, no. 000, pp. 8, 2023, http://dx.doi.org/10.1016/j.carbon.2023.118081.

[48] W. Chen, C. Li, D. Wang, S. Gao, C. Zhang, H. Guo, W. An, S. Guo, and G. J. P. C. C. P. Wu, “A dual ultra-broadband switchable high-performance terahertz absorber based on hybrid graphene and vanadium dioxide,” Physical Chemistry Chemical Physics, vol. 25, no. 30, pp. 20414-20421, 2023, http://dx.doi.org/10.1039/D3CP01312J.

[49] D. Y. Li, L. X. Liu, Q. W. J. A. a. m. Wang, and interfaces, “Functional Polyaniline/MXene/Cotton Fabrics with Acid/Alkali-Responsive

and Tunable Electromagnetic Interference Shielding Performances," ACS Applied Materials & Interfaces, no. 10, pp. 14, 2022, http://dx.doi.org/10.1021/acsami.2c00797.

[50] B. Zhao, P. Bai, M. Yuan, Z. Yan, B. Fan, R. Zhang, and R. J. C. Che, "Recyclable magnetic carbon foams possessing voltage-controllable electromagnetic shielding and oil/water separation," Carbon, vol. 197, pp. 570-578, 2022, http://dx.doi.org/10.1016/j.carbon.2022.06.010.

[51] Wei, Jingjiang, Yunfei Yang, Fei Pan, Kun Yang, Yanqing Wang, Zhihui Zeng, Qingyuan Wang, and Zhengyi Fu. "Hofmeister effect-inspired Ti3C2Tx MXene-based robust, multifunctional hydrogels." Composites Part A: Applied Science and Manufacturing 172, 107626, 2023, http://dx.doi.org/10.1016/j.compositesa.2023.107626.

[52] L. Mei, W. Ouyang, L. Xu, Y. Huang, Q. Liu, Y. Bai, Q. Lu, T. Luo, and Z. J. S. Wu, "Super Tough Multifunctional MXene/PAA-CS Double Network Hydrogels with High Mechanical Sensing Properties and Excellent EMI Shielding Performance," Small, vol. 21, no. 6, pp. 2410687, 2025, http://dx.doi.org/10.1002/smll.202410687.

[53] H. Meikang, Z. Danzhen, and S. C. E. M. B. T. R. J. K. Y. J. N. nanotechnology, "Electrochemically modulated interaction of MXenes with microwaves," Nature Nanotechnology, vol. 18, no. 4, pp. 373-379, 2023, http://dx.doi.org/10.1038/s41565-022-01308-9.

[54] Jiang, PZ., Deng, Z., Min, P. et al. Direct ink writing of multifunctional gratings with gel-like MXene/norepinephrine ink for dynamic electromagnetic interference shielding and patterned Joule heating. Nano Res. 17, 1585–1594, 2024, https://doi.org/10.1007/s12274-023-6044-9.

[55] Wei, Yuyi, Chuanshuang Hu, Zhenhua Dai, Yanfei Zhang, Weiwei Zhang, and Xiuyi Lin. "Highly anisotropic MXene@ Wood composites for tunable electromagnetic interference shielding." Composites Part A: Applied Science and Manufacturing 168, 107476, 2023, https://doi.org/10.1016/j.compositesa.2023.107476.