Recent Advances in MXene/Polyaniline-Based Composites for Electrochemical Devices and Electromagnetic Interference Shielding Applications

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Abstract: Due to serious global warming and environmental issues, the demand for clean and sustainable energy storage devices is significantly increased. Often accompanied by rapid growth of portable electronic vehicles and devices, massive electromagnetic wave pollution becomes unavoidable. To mitigate the above two issues, this mini-review summaries preparation methods and recent developments of MXene/polyaniline-based composites for their applications in electrochemical devices and electromagnetic interference shielding. Based on excellent synergistic effects between single compounds and designed hierarchical structures, MXene/polyaniline-based composites usually exhibit enhanced physical and chemical properties, showing great potentials in sustainable electrochemical properties and electromagnetic wave protections for human health as well as normal operation of precise electronic devices.

Introduction

Along with environmental pollution and the energy crisis, the demand for clean and sustainable energy is significantly increased.1 Energy storage devices are environmentally friendly, cost-effective, and powerful, which promote the development of electronic vehicles and portable electronics.2 Often accompanied by rapid growth of portable electronic vehicles and devices, massive electromagnetic wave pollution becomes unavoidable and thus has detrimental impacts on public health and the surrounding environment.3 To mitigate electromagnetic (EM) wave pollution, electromagnetic interference (EMI) shielding and EM wave absorption materials are usually used such that human health can be protected as well as normal operation of precise electronic devices.4

MXenes, an emerging class of 2D transition metal carbides, nitrides, and carbonitrides as first published by Gogosti et al. in 2011,5 are usually prepared by selective etching of the A layers (Group III A or IV A) from MAX phases with a general formula of $M_{n+1}X_nT_x$, where M is an early transition metal, X is C and/or N, T$_x$ represents surface functional groups (e.g., −OH, −F, and/or −O), and $n = 1, 2, or 3$ (see Figure 1a).5,6 Thus, MXenes possess unique properties,7 such as high specific surface area, high electrical conductivity, surface hydrophilicity, and high electrochemical activity (see Table 1). It shows great potential in the applications of electrochemical devices, EMI shielding, and EM wave absorption. Due to the rich surface functional groups (such as −O, −OH, and/or −F), MXene can provide nucleation sites to obtain composites by the combination with other nanostructured polymers.8,9 Moreover, polyaniline (PANI), a typical pseudocapacitive conducting polymer, has been widely investigated because of its ease of synthesis, excellent thermal and environmental stability, low cost, and attractive redox and simple acid/base doping/dedoping (see Figure 1b and Table 1).9 Nanostructured PANI can be easily introduced among layered structures of MXene to form hierarchical MXene/PANI-based composites when MXene acts as an active material with a large surface area and a framework (see Figure 1c).7b

Recently, MXene/PANI-based composites have aroused considerable interest for applications in supercapacitors,6a,b,7d,11b sensors,7c,10c,d,14 sodium ion batteries,12a absorbers,15 EMI shielding,4 and EM wave absorption.3a To satisfy the demand for sustainable electrochemical devices and mitigate EM wave pollution, this mini-review discusses preparation methods and applications of MXene/PANI-based composites in electrochemical performance, EMI shielding, and EM wave absorption. What’s more, the analysis of electrochemical performance and EM performance of MXene/PANI-based...
composites is based on rational designed hierarchical structures and excellent synergistic effects between single compounds of the composites. Hence, this mini-review provides new insights into the preparation of MXene/PANI-based composites as well as the practical applications.

### PREPARATION STRATEGIES OF MXENE/PANI-BASED COMPOSITES

MXene/PANI-based composites can be obtained by many approaches, such as in situ polymerization, interfacial polymerization, electropolymerization, self-assembly, layer-by-layer assembly, vacuum-assisted filtration, mechanical blending, dip-coating, spray coating, and hydrothermal reaction and so on (see Table 2). In this section, the above preparation strategies of MXene/PANI-based composites will be discussed.

In situ polymerization is one widely used method to prepare MXene/polyaniline-based composites. A general procedure is usually as follows (see Figure 2): the delaminated Ti₃AlC₂ powders are dispersed in a certain HCl solution, followed by addition of aniline monomers to obtain a mixed solution as stirred in an ice–water bath (0–5 °C). Then, ammonium persulfate (APS)-dispersed HCl solution is gradually added into the above mixed solution. The resulting dispersed solution is magnetically stirred for several hours at 0–5 °C. Finally, the MXene/PANI-based composite is obtained with the treatments of centrifuging, washing and vacuum-drying. In a polymerization process, positively charged aniline and negatively charged functional groups (e.g., Ti–OH⁻ and Ti–F⁻) on the surface of MXene would attract each other. The electrostatic interactions promote nanostructured PANI anchored on the surface of MXene, and then the formed PANI nanostructures prevent MXene layers from stacking and collapsing. Moreover, VahidMohammadi et al. demonstrated

![Figure 1](image-url)

Figure 1. (a) Schematic of the exfoliation process for Ti₃AlC₂. (b) Doped PANI. (c) Schematic overview of preparation of MXene/PANI-based composites. Panel (a) is adapted with permission from ref 5. Copyright 2011 John Wiley & Sons, Inc.
that the MXene/PANI hybrid can be fabricated through an oxidant-free in situ polymerization process.\textsuperscript{11b} Usually, ammonium persulfate is needed to initiate a polymerization process of conducting polymers, whereas aniline monomers can polymerize without an oxidant on the surface of MXene as long as a charge transfer occurs between aniline and MXene.\textsuperscript{17} Using in situ polymerization, PANI can be well-dispersed onto the surface of MXene. Nanostructured PANI can easily anchor on the surface of MXene, and thus a large number of the resulting PANI can prevent the MXene nanosheets from stacking together.\textsuperscript{10c} Layer-by-layer assembly method is another facile method to synthesize MXene/PANI-based composite using electrostatic interactions between PANI and the surface of MXene.\textsuperscript{11c} The hydrophilicity and negative charges on the surface of MXene provide the polymerization conditions for the combination with positively charged PANI.\textsuperscript{10d} For example, Yin et al. developed a multifunctional MXene/PANI composite textile by a combination of 1D PANI nanowires and 2D MXene nanosheets onto a carbon fiber fabric substrate based on the layer-by-layer assembly method (see Figure 3).\textsuperscript{10a} Moreover, self-assembly and in situ assembly methods are also used in the fabrication of MXene/PANI-based composites.\textsuperscript{7a,10b,14,18} Wang et al. took solvent-assisted self-assembly and a redispersion strategy to prepare PANI/MXene inks and then obtained PANI/MXene composite films via an evaporation-induced assembly process.\textsuperscript{10b} Chen et al. used DL-tartaric acid assembled on the surface of MXene to achieve supramolecular self-assembly and then obtained a PANI/MXene composite using the electronegative oxygen groups that can induce the polymerization of PANI.\textsuperscript{7a} Vacuum-assisted filtration is usually used to obtain free-standing films.\textsuperscript{4,19} In a typical vacuum-assisted filtration process, the PANI dispersion and the colloidal solution of MXene are mixed and stirred evenly, and then the MXene/PANI composite is dried and obtained by using vacuum-assisted filtration.\textsuperscript{19b} For example, Zhang et al. dissolved a certain amount of c-PANI, Ti$_3$C$_2$Tx, and CNF-P in DMF,
sonicated the above solution for 30 min, and obtained MXene/PANI composite films by vacuum-assisted filtration. Wang et al. added different amounts of Fe₃O₄@PANI powder to Ti₃C₂Tₓ solution, achieved a well-mixed solution after continuous stirring, and obtained a composite film by vacuum-assisted filtration (see Figure 4). In short, high-quality free-standing MXene/PANI composite films can be prepared by vacuum-assisted filtration, but the whole process usually needs a long time (e.g., overnight).

In addition, other preparation strategies of MXene/PANI-based composites are also developed. For example, Lei et al. synthesized PANI onto Ti₃C₂Tₓ/CNZFO powder via interfacial polymerization. Neamper et al. produced nanstructured PANI on the MXene surface by electropolymerization. Kumar et al. prepared the MXene/PANI composite by mechanical blending of PANI powder with MXene powder in a 1:1 weight ratio. Jia et al. fabricated MXene@PANI/mPP foam beads via a dip-coating approach and obtained foam beads with different MXene content by repeating the dip-coating process several times. Raagulan et al. fabricated the Ti₃C₂Tₓ-PAT-PANI-PpAP composite by a cost-effective spray-coating technique. Li et al. added aniline solution into the Ti₃AlC₂ solution under ultrasonic treatment for 6 h and obtained a composite via a hydrothermal reaction at different temperatures.

### ELECTROCHEMICAL PROPERTIES OF SUPERCAPACITORS

Supercapacitors (SCs) have drawn substantial interest in portable electronic devices and electric vehicles because of their high power density, long cycle life, fast charging and discharging rates, safe operation, and low maintenance costs. The electrochemical properties of electrode materials in SCs can be evaluated by a potential window, specific capacity, energy density, power density, and cyclic stability and so on (see Table 3). In this section, the electrochemical properties of MXene, PANI, and MXene/PANI-based composites used as electrode materials of pseudocapacitive SCs are discussed in terms of a three-electrode system, a symmetric device, and an asymmetric device (Figure 5), respectively.

The three-electrode system is a conventional approach to evaluate the electrochemical performance of electrode materials.

### Table 3. Electrochemical Properties of MXene, PANI, and MXene/PANI-Based Composites Used as Electrode Materials for Supercapacitors

| materials | electrolytes | potential window | specific capacity | energy density | power density | cyclic stability |
|-----------|--------------|------------------|-------------------|----------------|---------------|-----------------|
| Ti₃C₂Tₓ//PANI@rGO  | 3 M H₂SO₄ | 1.45 V | 57 F/g (at 5 mV/s) | ~17 Wh/kg | ~0.207 kW/kg | 88% after 20000 cycles (at 100 mV/s) | 6a |
| Ti₃C₂Tₓ//PANI@Ti₃C₂Tₙ | 3 M H₂SO₄ | 1.2 V | 87.3 F/g (at 10 mV/s) | 50.6 Wh/L | 1.7 kW/L | 19c |
| graphitic/Ti₃CTₓ//PANI//graphene | 1 M H₂SO₄ | 1.8 V | 94.5 F/g (at 1 A/g) | 42.3 Wh/kg | 0.95 kW/kg | 94.25% after 10000 cycles (at 10 A/g) | 2b |
| Ti₃C₂Tₓ//rGO/CNT//PANI | 3 M H₂SO₄ | 1.45 V | 116.9 F/g (at 10 mV/s) | 70 Wh/L | 111 kW/L | 80% after 10000 cycles (at 100 mV/s) | 12b |
| PANI/Ti₃C₂Tₓ//Ti₃C₂Tₙ | 1 M H₂SO₄ | 1.4 V | 82.6 F/g (at 10 mV/s) | 65.6 Wh/L | 1.687 kW/L | 87.5% after 5000 cycles (at 20 mA/cm²) | 10b |
| graphitic/Ti₃C₂Tₓ//PANI//TₙC₃Tₓ | 1 M H₂SO₄ | 1.5 V | 15.6 Wh/kg | 0.711 kW/kg | 72.8% after 5000 cycles (at 10 A/g) | 7d |
| Ti₃C₂Tₓ//active carbon | 7 M KOH | 1.2 V | 563 F/g (at 0.5 A/g) | 22.67 Wh/kg | 0.217 kW/kg | 90.82% after 10000 cycles (at 5 A/g) | 6b |
| Ti₃C₂Tₓ//PANI-NTs//Ti₃C₂Tₓ//PANI-NTs | 1 M H₂SO₄ | 1.8 V | 300.8 F/g (at 0.1 A/g) | 13.2 Wh/kg | 1.61 kW/kg | 81.8% after 4000 cycles (at 1 A/g) | 1 |
| Ti₃C₂Tₓ//PANI/Ti₃C₂Tₓ//PANI | 3 M H₂SO₄ | 1 V | 130 F/g (at 2 mV/s) | 79.8 Wh/L | 0.575 kW/L | 61% after 10000 cycles (at 5 mA/cm²) | 11b |
| Ti₃C₂Tₓ//DLTA//PANI/Ti₃C₂Tₓ//DLTA//PANI | PVA-H₂SO₄ gel | 0.8 V | 710 mF/cm² (at 1 mA/cm²) | 0.063 mWh/cm² | 0.398 W/cm² | 61.5% after 10000 cycles (at 5 mA/cm²) | 7a |
| N-Ti₃C₂Tₓ//PANI-420 | 0.5 M H₂SO₄ (vs Hg/HgCl₂) | 0.5 V | 228 mF/cm² (at 5 mV/s) | 85% after 1000 cycles (at 1 mA/cm²) | 91.6% after 5000 cycles (at 5 A/g) | 2a |
| Ti₃C₂Tₓ//PANI | 1 M H₂SO₄ | 0.8 V (vs Ag/AgCl) | 556.2 F/g (at 0.5 A/g) | 99.6% after 3000 cycles (at 3 A/g) | 13 |
| PANI-TₙC₃Tₓ | 1 M Na₂SO₄ | 0.6 V (vs Ag/AgCl) | 164 F/g (at 2 mV/s) | 94% after 8000 cycles (at 1 A/g) | 7b |
| PANI@TiO₂//Ti₃C₂Tₓ | 1 M KOH | 0.7 V (vs Ag/AgCl) | 188.3 F/g (at 10 mV/s) | 98% after 5000 cycles (at 10 mV/s) | 18 |
| Ti₃C₂Tₓ//PANI-NFs | 3 M H₂SO₄ | 0.95 V (vs Ag/AgCl) | 645.7 F/g (at 10 mV/s) | 10000 cycles (at 20 A/g) | 19b |
| Ti₃C₂Tₓ//CNT//PANI | 1 M H₂SO₄ | 1 V (vs Hg/Hg,SO₄) | 429.4 F/g (at 1 A/g) | 428.7 mW/cm² | 95.5% after 20000 cycles (at 100 mV/s) | 6b |

Figure 4. Fabrication diagram of the Ti₃C₂Tₓ/c-PANI EMI shielding composite films. Adapted with permission from ref 4. Copyright 2019 Elsevier Ltd.
of SCs, consisting of a working electrode, a reference electrode, and a counter electrode. Usually, a MXene/PANI-based composite is used in the working electrode, Ag/AgCl (or Hg/HgCl2, Hg/Hg2SO4) is used as the reference electrode, and platinum electrode (or glass carbon) is used in the counter electrode. Compared with the two-electrode system, the three-electrode system can maintain the steady potential of the working electrode and thus facilitate the evaluation of the electrochemical properties of the working electrode. For example, PANI-Ti3C2 composites were synthesized via in situ polymerization and can be used as a high-performance supercapacitor electrode material as tested by a three-electrode system.\(^\text{15}\) The results showed that the introduction of amino groups in PANI to Ti3C2 improved not only electric conductivity but also surface wettability and thus improved the electrochemical properties because of the synergistic effect between PANI and Ti3C2.\(^\text{15}\) To increase amino groups, Wu et al. used the amino group of amino-Ti3C2 as the active site to react with the amine nitrogen of PANI chains.\(^\text{2a}\) As a result, the electrochemical activity sites and charge transport can be further increased because of the synergistic effect between N-Ti3C2 and PANI, and thus the electrochemical properties of N-Ti3C2/PANI for SCs improved.\(^\text{2a}\)

For PANI-Ti3C2 composites, hierarchical structures can also influence electrochemical properties. Wu et al. introduced PANI nanotubes onto the interlamination of ultrathin graphene-like Ti3C2 nanosheets and found that the dispersed PANI nanotubes showed an open and interlocking structure preventing Ti3C2 nanosheets from stacking and collapsing.\(^\text{1}\) Another type of MXene Ti1C2T4 is used to combine with PANI to fabricate Ti1C2T4/PANI composites.\(^\text{6c,17b,11b}\) The experimental results indicate that hierarchical structures and the synergistic effect between PANI and Ti1C2T4 are attributed to the high performance of Ti1C2T4/PANI composites used as electrode materials of SCs as tested in a three-electrode system.\(^\text{b}\)

To evaluate the feasibility of electrode materials used in practical SCs,\(^\text{19c}\) electrode materials of SCs are usually assembled into symmetric and asymmetric devices. Compared with asymmetric devices, symmetric devices usually show relatively narrow operating voltage window.\(^\text{10b}\) In a symmetric device, anode and cathode materials are the same and require chemical stability as used in electrolytes. The conducting polymers usually show the best electrochemical performance in acidic electrolytes under positive potentials.\(^\text{2a}\) Therefore, the target materials used in both anode and cathode need to be stable under negative or positive potentials. For example, Wu et al. fabricated Ti3C2/PANI-NTs-1 composites by decorating 2D Ti3C2 nanosheets with 1D hollow PANI-NTs, and these unique structures as combined from Ti3C2 and PANI-NTs-1 enlarge ion diffusion kinetics during the redox reaction.\(^\text{1}\) When the composite is used as advanced electrode materials for symmetric supercapacitors (SSCs), it can light up a 1.8 V LED, indicating its great potential in practical energy storage.\(^\text{1}\)

For asymmetric supercapacitors (ASCs), matching cathode materials with anode materials is still a challenge to improve the integral electrochemical performance of SCs, such as operating voltage window and energy density. Take MXene/PANI-based composites as cathode materials, for instance; Li et al. prepared a hierarchical PANI@MXene cathode with a PANI layer uniformly coated on a 3D porous MXene Ti1C2T4 network.\(^\text{19c}\) Compared with pure MXene, the integrated PANI@MXene heterostructure can enhance the electrochemical stability toward anodic oxidation, as demonstrated by first-principles calculations.\(^\text{16b,19c}\) Similarly, Wang et al. designed a scalable PANI/MXene cathode material decorated with PANI nanodots.\(^\text{2b}\) In this cathode material, the PANI nanoparticles not only work as high pseudocapacitive materials but also act as pillaring components for reducing MXene stacking and enabling electron and ion transport, thereby obtaining an excellent synergistic effect in the electrochemical performance of ASCs.\(^\text{2b}\)

In order to enhance electrochemical properties, many researchers introduced a third component into MXene/PANI-based composites to form ternary composites as used in ASCs. For example, Fu et al. reported that a graphene-encapsulated MXene Ti1CT4@PANI composite used as a cathode material can exhibit improved cycling stability and better electrochemical performance of ASCs owing to the robust hierarchical nanostructures and complementary synergistic effect between graphene-encapsulated Ti1CT4 and PANI.\(^\text{1b}\) Wang et al. successfully prepared a layered graphene-decorated 2D Ti1C2T4/polyaniline (GTP) nanocomposite, and GTP showed a superior capacitive performance, large voltage window, and good cycling stability based on the synergistic effect among three components when served as the cathode materials in ASCs.\(^\text{1b}\) In short, when used as cathode materials, MXene/PANI-based composites with hierarchical structures usually exhibit synergistic effects between MXene and PANI and thus improve the electrochemical performance of ASCs.

### ELECTROCHEMICAL PROPERTIES OF OTHER DEVICES

Recently, MXene/PANI-based composites have also been used as electrode materials for other electrochemical energy storage devices\(^\text{1,12a}\) and sensors.\(^\text{7c,10c,14}\) For electrochemical energy storage, the introduction of conducting PANI into MXene/PANI-based composites can prevent MXene nanosheets from restacking and agglomerating and thus improve electrochemical performance.
properties because of potential synergistic effects. For example, first-principles calculations were utilized to systematically investigate electrochemical properties, and the results showed the introduction of PANI into MXene/PANI composites can improve electric conductivity and maintain strong Na adsorption and high Na diffusion kinetics when used as anode materials for sodium ion batteries.\textsuperscript{12a} Yun et al. prepared a 2 μm thick thin film PNF/MXene electrode via a layer-by-layer assembly process and applied it for thin-film electrochemical energy storage.\textsuperscript{11a}

For sensors, MXene/PANI-based composites can be used as sensitive films to detect low content substances, such as NH\textsubscript{3},\textsuperscript{14} lactate,\textsuperscript{26c} or ethanol gas.\textsuperscript{10c} Generally, hierarchical MXene/PANI-based composites have abundant absorption sites and large specific surface area that facilitate a fast response and high sensitivity toward low content substances. For example, Li et al. prepared a flexible PANI/Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} hybrid-sensitive film-based gas sensor that exhibited excellent NH\textsubscript{3}-sensing properties to 20–80% relative humidity environments at a temperature range of 10–40 °C.\textsuperscript{14} Neampet et al. used a Pt/PANI/MXene nanocomposite for amperometric sensing of hydrogen peroxide and lactate, and this nanocomposite can provide a low detection limit of 1.0 μM.\textsuperscript{7c} Zhao et al. demonstrated high electrocatalytic sensitivity of PANI/Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} nanocomposites for ethanol gas via an integration of density functional theory simulations and bulk electro sensitive measurements.\textsuperscript{10c}

\section*{ELECTROMAGNETIC INTERFERENCE SHIELDING PROPERTIES}

In the development of electronic devices, EM waves are unavoidable during the normal performance in daily life.\textsuperscript{25} EM and EM wave pollutions become critical issues for public health and malfunctioning of electronic devices and thus restrict the wide use of portable electronics.\textsuperscript{16a,19a} EMI shielding materials and EM wave absorption materials are usually chosen to mitigate the influence of EM waves. To date, various types of materials have been utilized in preventing EM wave pollution.\textsuperscript{26}

For metals, copper, aluminum, silver, nickel, and stainless steel have been used as a shield, while these metals have certain limitations, such as high density, difficult machining, and high corrosion susceptibility.\textsuperscript{26a,c} Many heterogeneous composites with conducting fillers (e.g., carbon nanotubes (CNTs), graphene, reduced graphene oxide (rGO), and MoS\textsubscript{2}),\textsuperscript{26d} magnetic fillers (e.g., Fe\textsubscript{3}O\textsubscript{4}, Fe\textsubscript{2}O\textsubscript{3}, and barium ferrite),\textsuperscript{19a,26c} and dielectric fillers (e.g., BaTiO\textsubscript{3}, TiO\textsubscript{2}, and PbTiO\textsubscript{3})\textsuperscript{15,26c,26a} have been applied in the EMI shielding application instead of metals because of their advantages (e.g., low weight, better environmental stability, and excellent corrosion-resistant properties).\textsuperscript{26c–f}

Generally, for EMI shielding, there are three kinds of mechanisms for EMI shielding: (1) to reflect radiation; (2) to absorb EM radiation; (3) have multiple internal reflections (see Figure 6).\textsuperscript{25} Usually, EM reflection is due to mobile charge carriers in EMI shielding materials, whereas EM absorption is because of electric and/or magnetic dipoles.\textsuperscript{34} Thus, absorption, reflection, and multiple reflections are three key factors for the EMI shielding behavior of materials.\textsuperscript{21} High electrical conductivity usually determines the reflection and absorption performance of EMI shielding materials. Moreover, the structural design of EMI materials is also important to minimize the secondary EMI pollution.\textsuperscript{15}

Since 2011, Gogotsi et al. have reported a novel 2D material named MXene\textsuperscript{3} and found that 2D Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} MXene can be used in the EM field because of its unique layered structures, providing many conductive paths.\textsuperscript{25} Although the Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} film (a 45 μm thickness) can exhibit EMI SE of 92 dB among synthetic materials with comparable thickness,\textsuperscript{25} the high dielectric constant of Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} will cause impedance mismatch, limiting its further improvement in the electromagnetic performance.\textsuperscript{16b} PANI is also used as EMI shielding material because of its low cost, easy doping/dedoping, low environmental impact, and easy synthesis. Synergies between Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} and PANI, such as interface polarization and dipole-oriented polarization, multiple conductive paths, improved impedance matching, and increased dielectric loss are conductive to attenuation of EM waves.\textsuperscript{3b,16a,22,23} Therefore, many researchers show great interest in the MXene/PANI-based nanocomposites as well as their application in EMI shielding (see Table 4).\textsuperscript{3a,4,10a,19a,20,21,24,25}

Generally, EMI shielding effectiveness (SE) describes the ability of materials to shield EM waves, when the reflection and absorption coefficient are quantitative descriptions of EM waves reflection and absorption.\textsuperscript{4} For example, binary MXene/PANI-based composites have been used in the application of EMI shielding. Kumar et al. reported that a lightweight Ti\textsubscript{3}C\textsubscript{2}/PANI composite had a good enhanced EMI SE of ≈23 dB with the sample thickness of 1.5 mm and found that the laminated MXene with a superior specific surface area plays a dominate role in the enhanced microwave absorbing performance of Ti\textsubscript{3}C\textsubscript{2}/PANI composite.\textsuperscript{3b} Based on optimized organic/inorganic (1D/2D) continuous conductive network, Yin et al. developed a flexible, lightweight, and multifunctional PANI/MXene-based composite textile possessing an outstanding electrical conductivity (325 S/m) and an excellent EMI shielding performance (SE of ≈35.3 dB) at the thickness of only 0.376 mm.\textsuperscript{10b} Zhang et al. fabricated ultrathin and flexible Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x}/c-PANI composite films with EMI SE of 36 dB at the thickness of 40 μm and showed that the shielding mechanism changed from the equal shielding mechanism to the reflection-dominated shielding mechanism as the content of Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x} in Ti\textsubscript{3}C\textsubscript{2}T\textsubscript{x}/c-PANI composite increased.\textsuperscript{4}

To further improve the EMI shielding properties, several researchers show interest in the fabrication of ternary or quaternary MXene/PANI-based composites. For example, Jia et al. constructed compressible MXene@PANI/mPP composite foams, and these composite foams showed an absorption-dominated shielding mechanism with effective EMI SE of ~23.5–39.8 dB and low R coefficient of ~0.20–0.31 after encapsulating with PDMS.\textsuperscript{20} Raagulan et al. reported that a
MXene-PAT-PANI-PpAP composite had an EMI SE of 45.18 dB at 8.2 GHz. They found that reduced form of MXene increased EMI SE, and the absorption was enhanced by the antiformalike structures. Wang et al. prepared a flexible and lightweight Ti₃C₂Tx/Fe₃O₄@PANI composite film by vacuum-assisted filtration, and this ternary composite achieved an EMI SE of 62 dB with the film thickness of 16.7 μm, which exhibited great potential for applications in packaging, wearable electronic equipment, and military fields. Yin et al. prepared multilayer structured PANI/MXene/CF fabric via a layer-by-layer strategy, and this fabric realized a high EMI SE (26.0 dB) and specific EMI SE (135.5 dB cm²/g). Moreover, this fabric maintained flexibility, air permeability and washability of textile substrates, showed an absorption-dominated shielding mechanism and thus effectively decreased secondary EM wave pollution.

**ELECTROMAGNETIC WAVE ABSORPTION PROPERTIES**

To alleviate EM pollution, one alternative approach is to use EM wave absorption materials. Ideal EM wave absorption materials need to exhibit excellent properties, such as lightweight, strong absorption peaks, broad effective absorption bandwidth, good interfacial polarization, EM wave attenuation capability, proper impedance matching, and so on. Recently, MXene has been used in EM wave absorption because of its excellent electrical conductivity, dielectric loss, high specific surface area, mechanical rigidity, and stable chemical properties (see Table 1). Meanwhile, PANI as a conducting polymer is also a EM wave absorption material with electrical loss. To enhance EM wave absorption properties, MXene/PANI-based composites have been studied by many researchers (see Table 5). For example, Wei et al. fabricated a sandwich-like Ti₃C₂Tx/PANI composites by the in situ polymerization of aniline monomers onto Ti₃C₂Tx, showing an effective absorption bandwidth (>90%) ranging from X-band (8–12.4 GHz) to Ku-band (12.4–18 GHz) because of synergistic effect between Ti₃C₂Tx and PANI and exhibiting great potential in serving as microwave absorption materials.

Table 4. EMI Shielding Properties of MXene/PANI-Based Composites

| materials                  | electrical conductivity (S/m) | EMI SE (dB) | thickness (mm) | band frequency (GHz) | ref  |
|----------------------------|-------------------------------|-------------|----------------|----------------------|------|
| MXene@PANI/mPP             |                               | ~23.5–39.8 | 12             | 5.38–8.17            | 20   |
| Ti₃C₂Tx/Fe₃O₄@PANI         | 59900                         | 58.8        | 0.0167         | 8.2–12.4             | 19a  |
| PANI/MXene/CF              | 24.57                         | 26.0        | 0.55           | 8.2–12.4             | 24   |
| MXene/PAT/PANI-PpAP        | 781.3                         | 45.18       | 0.8            | 8.2                  | 21   |
| Ti₃C₂Tₓ/CF                | 22.7                          | 1.5         | 10.8           | 8.2–12.4             | 3a   |
| Ti₃C₂Tx/c-PANI             | 2440                          | 36          | 0.04           | 8.2–12.4             | 4    |
| PANI/MXene                 | 325                           | 35.3        | 0.376          | 8.2–12.4             | 10a  |

Table 5. Electromagnetic Wave Absorption Properties of MXene/PANI-Based Composites

| materials                  | reflection loss (dB) | effective absorption bandwidth (GHz) | thickness (mm) | ref  |
|----------------------------|----------------------|--------------------------------------|----------------|------|
| Ti₃C₂Tₓ/CNZFO/PANI         | −37.1 (10.2 GHz)     | 4.1 (8.2–12.3 GHz)                  | 2.2            | 3b   |
| Ti₃C₂Tₓ/TiO₂/PANI          | −56.3 (13.8 GHz)     | 4.28 (11.99–16.27 GHz)              | 1.8            | 16a  |
| Ti₃C₂Tₓ/TiO₂/PANI          | −65.61 (13.92 GHz)   | 5.92 (11.84–17.76 GHz)              | 2.18           | 23   |
| Ti₃C₂Tₓ/Fe₃O₄/PANI         | −40.3 (15.3 GHz)     | 5.2 (12.8–18 GHz)                   | 1.9            | 22   |

In summary, this mini-review introduces preparation methods and recent developments of MXene/polyaniline-based composites for their applications in electrochemical devices and EMI shielding. When used as electrode materials, MXene/polyaniline-based composites show excellent electrochemical properties in supercapacitors, lithium ion battery, sodium ion battery and sensors because of hierarchical structures and synergistic effects by the combination of MXene and PANI. Moreover, MXene/polyaniline-based composites can also be applied in the field of preventing EM wave pollution based on unique properties of MXene and PANI (e.g., good electrical conductivity and dielectric loss). In the future, the widespread use of portable electronic vehicles and devices is a general trend, and it is necessary to design electrochemical energy storage devices with massive power density and life span. Thus, construction of electrode materials with stable hierarchical structures and synergistic effects during an electrochemical process is crucial for energy storage devices. Of course, EM wave pollution is also a huge challenge when abundant portable electronic vehicles and devices are used. By optimizing hierarchical structures and introducing more components, excellent composites can be achieved to mitigate EM wave pollution. Moreover, MXene has...
good environmental stability, and PANI is also an environmentally friendly polymer. Thus, a MXene/PANI-based composite has less environmental impact during its various applications. Based on controllable hierarchical structures and synergistic effects between MXene and PANI, a MXene/PANI-based composite shows great commercial potential in the future. All in all, rationally designed hierarchical MXene/polyaniline-based composites are promising candidates for electrochemical devices, EMI shielding, and EM wave absorption and also provide great potential in the practical applications.

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