TOPICAL REVIEW

Exploring MXene-based materials for next-generation rechargeable batteries

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Abstract
MXenes have attracted widespread attention as a kind of emerging 2D material with unique physical and chemical properties. Due to their low adsorption energy and diffusion barrier for some metal ions, some MXenes have become very promising electrode materials for metal-ion batteries. Because of their unique structures and mechanical properties, MXenes are also used in alkaline metal batteries and lithium-sulfur batteries to maintain the integrity of the electrode structure and improve the stability of the battery’s performance. Therefore, MXenes have been widely used in various new-type battery systems. In order to understand the role of MXenes in various post-lithium-ion batteries and evaluate their application potential in these batteries, in this review, the application of MXenes in various post-lithium-ion batteries is comprehensively summarized. In addition, since the preparation methods and conditions have a great impact on the performance of MXenes, various methods for preparing MXenes have also been summarized. Furthermore, with regard to the current development situation of MXenes, we have also expressed our opinions and discussed their development directions in order to enlighten the readers.

1. Introduction
Since the successful preparation of graphene in 2004, 2D materials have attracted extensive attention due to their attractive physicochemical and mechanical properties [1]. In 2011, a new 2D material labeled Ti$_3$C$_2$ was successfully prepared, which aroused great interest on a worldwide scale [2]. Since then, various materials with similar structures have been continuously developed to form a large family known as MXenes. MXenes are usually generated from MAX phase materials and their analogs by selectively etching away the ‘A’ layer from the MAX phases [3]. As shown in figure 1(a), the ‘A’ atomic layer is removed from the layered MAX material under the action of an etching agent to produce the corresponding 2D MXene material, because the interaction force of the M–A bond is weaker than that of the M–X bond [4]. During the etching process, as the ‘A’ atoms are removed, some ions or molecules in the etchant will react with the newly generated surface so that the surface of MXenes often has OH, O, F or other functional groups attached [5]. Thus, MXenes can be expressed by the formula M$_n$+$\frac{1}{2}$X$_n$T$_x$, where M represents an early transition metal, such as Ti, V, etc, X is carbon and/or nitrogen and T stands for surface functional groups [6–8]. Similar to graphene, MXenes can also obtain outstanding electrical conductivity and intriguing mechanical properties and are also capable of changing their properties through structural control and heteroatom doping [6, 9]. In addition, MXenes have unique magnetic and optoelectronic properties as well as good affinity originating from their surface functional groups [9, 10]. In view of the diversity of MXenes and their characteristic properties, they have shown tremendous potential for application in many fields, such as catalysis, sensor technology, biomedicine, water purification, gas adsorption and other new energy fields [5, 10].
At present, lithium-ion batteries (LIBs) occupy a dominant position in the market of electronic devices due to their high-energy density, long cycle life and environmental benignity [12, 13]. However, LIBs are facing the problem of a shortage of lithium resources and high costs, which seriously restricts their further development [14]. Therefore, for the sake of alleviating the demand for energy storage devices, it is of great urgency and significance to develop next-generation rechargeable batteries to supersede LIBs. In recent decades, with the advantages of low price and abundant resources (figure 1(b)), sodium-ion batteries (SIBs), potassium-ion batteries (PIBs), magnesium-ion batteries (MIBs), calcium-ion batteries (CIBs), aluminum-ion batteries (AIBs), zinc-ion batteries (ZIBs), etc., have been thoroughly researched to take the place of LIBs, and gratifying progress has been made. In addition, due to the limitations of the materials currently used in LIBs, their energy density and dynamic performance are not ideal. Thus, developing some next-generation lithium-based batteries with higher performance is also imperative. Given this, the development of lithium-metal batteries (LMBs), lithium-sulfur batteries (LSBs) and lithium-oxygen batteries (LOBs) is in full swing. However, the intrinsic drawbacks of these batteries have not yet been resolved, restricting their commercial application. One of the pivotal reasons is that suitable electrode materials have not been found. Inspiringly, the emergence of MXenes, which have proved to have excellent electrochemical properties, allows researchers to see their potential. According to theoretical simulations and calculations, \( \text{Li}^{+}, \text{Na}^{+}, \text{K}^{+}, \text{Mg}^{2+}, \text{Ca}^{2+} \) and other ions can quickly migrate inside MXenes. In other words, MXenes have low ion diffusion barriers, which contributes to improving the rate performance of ion batteries [15–17]. Hence, MXene is a promising electrode material for ion batteries. Moreover, many studies have proved that MXene materials can effectively inhibit the growth of metal dendrites, opening up a new way for the commercial application of metal-based batteries [18, 19], such as LMBs, LSBs, LOBs, sodium-metal batteries (SMBs) and potassium-metal batteries (PMBs). In addition, studies have shown that the unique structural and physicochemical properties of MXenes can effectively inhibit the shuttle effect of polysulfides, which makes MXenes an effective component of LSB electrodes and separators [20]. Furthermore, the good conductivity of MXenes is advantageous for electrodes. Therefore, MXenes have become extremely popular materials for application in a variety of batteries.

Recently, due to the explosive growth of works concerning MXenes and metal-ion batteries, several reviews have been conducted. Aslam et al.'s work mainly introduced the application of MXenes in supercapacitors and various non-lithium-ion (Na\(^+\), K\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Al\(^{3+}\)) batteries [21]; Dong et al.'s work focused on the relationship between MXene-based nanostructures and the performance of metal-ion batteries (Li\(^+\), Na\(^+\), K\(^+\), Zn\(^{2+}\), Mg\(^{2+}\), Ca\(^{2+}\)) [22]; Greaves et al. paid more attention to the application of MXene-based anodes in metal-ion batteries (Li\(^+\), Na\(^+\), K\(^+\), Mg\(^{2+}\), Ca\(^{2+}\), Al\(^{3+}\)) and mentioned the application of MXenes in metal-ion hybrid capacitors [23]. Obviously, these works all involve the application of MXenes in various metal-ion batteries, effectively reflecting the promising prospects of MXenes in these fields. In general, post-lithium-ion batteries mainly include two categories: the first type is other metal-ion batteries and the second type is other lithium-based batteries with superior performance, including LMBs, LSBs and LOBs. None of the above works involves the second type of batteries. In our review, not only has the application of MXenes in various metal-ion batteries been summarized, but their application in LMBs, LSBs and LOBs has been given equal importance. In addition, we introduce the related content of the application of MXenes in SMBs and PMBs. In this review, we first briefly introduce various synthesis methods of MXenes and their properties related to electrochemical performance. Then, we focus on the recent application of MXenes in various non-lithium-ion batteries, including SIBs, PIBs, MIBs, LSBs, ZIBs, AIBs, LMBs, SMBs, and other ion batteries.
PMBs, LOBs, etc, and discuss the effects of the preparation methods and structural characteristics of MXenes on their electrochemical performance. Finally, we also point out the current problems and challenges of MXene-based electrodes in this review, and propose the possible development directions of MXene materials in the future. It is expected that MXenes will still provide immense scope for further research, to enable them to become practical electrode materials for commercial non-lithium ion batteries.

2. Synthesis methods of MXenes

The properties of prepared MXenes may vary significantly under different conditions. On the one hand, different etching environments have a great influence on the surface functional groups of MXenes [24]. According to theoretical analysis, it is believed that oxygen-terminated MXenes have better electrochemical storage performance, so MXenes as electrode materials of metal-ion batteries are more likely to be equipped with oxygen-terminated surfaces [16]. Through theoretical calculations, Wang et al proved that Ti3C2S2 and Ti3C2O2 are more suitable as host materials for sulfur cathodes than Ti3C2F2, Ti3C2Cl2 and Ti3C2N2 [25]. Lee et al also compared the performance of Ti3CO2 and Fe2CS2 as electrodes of AIBs using calculations [26]. The results showed that compared to Ti3CO2, the capacity of Fe2CS2 increased by 2.2 times and the diffusion coefficient of aluminum ions in Fe2CS2 increased by more than 20 000 times. These theoretical studies prove that the surface functional groups have a huge influence on the electrochemical performance of MXenes. In addition, due to the successful application of the Lewis acid molten salt etching method, MXenes with specific functional groups (Cl, Br, I) were successfully prepared. Li et al applied these three functional group-terminated MXenes to zinc-ion batteries to evaluate the influence of different functional groups on the electrochemical performance of MXenes [27]. The results revealed that Br-terminated and I-terminated MXenes exhibited better electrochemical performance. However, MXene prepared by various currently prevalent methods contains either fluorine or chlorine. There is an urgent need to develop some more convenient and optimized preparation methods. On the other hand, experimental factors, such as the solution concentration, reaction time and temperature all play important roles in the morphology, internal defects and yield of the prepared MXenes. It has been reported that defects in MXenes tend to react with active cations, resulting in the first coulombic efficiency of batteries being unsatisfactory [28]. Therefore, the preparation of MXenes has a critical impact on their electrochemical properties. Before discussing the application of MXenes in various batteries, it is necessary to first understand their diverse synthesis methods.

The earliest and most commonly used method to prepare MXene materials was hydrofluoric acid (HF) etching. In a typical preparation process, a MAX phase is immersed in an aqueous solution of HF with a specific concentration, and then the corresponding MXene can be obtained after a certain period of time at a certain temperature. If sonication is used, multi-layer MXenes will delaminate into few-layer or single-layer MXenes. A typical process for preparing MXene nanosheets from a MAX phase is shown in figure 2(a). For example, by immersing Ti3AlC powder in a 10% HF aqueous solution, the corresponding Ti3C MXene can be harvested after 10 h at room temperature [29]. Figure 2(b) shows a typical SEM image of MXene whose layered structure can be clearly seen. Compared with Ti-based MXenes, V-, Gr-, Nb- and Ta-based MXenes require more rigorous conditions, that is, longer time, higher concentration or higher temperature will be obtained, caused by different bond energies between different metals and Al [4, 28]. Similarly, MXenes containing N are generally more difficult to synthesize than MXenes containing C, which explains why fewer transition metal nitrides have been successfully synthesized [30]. This method can be applied to almost all MAX materials whose A is Al. To date, Ta2C3T3, TiNbCT3, Ti3CN, NbC3, Nb(Ti, Nb)3, Nb3ScZr2, AlC3, etc, have been successfully prepared by HF etching [31–33]. Furthermore, some MAX analogs such as Mo2Ga3C can also synthesize the corresponding MXene by HF etching. The difference is that the etched atom is Ga instead of Al [34].

Obviously, considering safety, the strong corrosiveness and toxicity of HF are not suitable for large-scale use. For this purpose, a milder etchant needs to be developed. A simple and effective strategy is to try to reduce the concentration of HF. Based on this idea and similar reaction principles, HF-containing and HF-forming etchants, which are safer than HF etchant, have been developed successively [4]. The typical representative of HF-containing etchants is NH3HF2, which was used to etch Ti3AlC2 by Halim et al in 2014 [37]. Differing from the ordinary MXenes formula, the product was expressed as (NH3)x(NH4)yTi3C2(OH)zFy, because NH3 and NH4+ intercalated into the space between the MXene sheets during the etching process. Due to the presence of NH3 and NH4+, the larger interlayer spacing obtained by NH3HF2 etching compared with the HF etching method, which is beneficial for the delamination of multilayer MXenes and the insertion and transfer of metal ions [30]. An HF-forming etchant mainly consists of a fluorine-containing salt and strong acid excluding HF acids, such as LiF + HCl [38, 39]. Li and other metal cations play the same role as NH3 and NH4+ [3, 30]. It is worth mentioning that HF-containing or HF-forming etchants in conjunction with sonication treatment can obtain MXene nanosheets in one step,
while using HF etching usually requires two steps to obtain few-layer MXenes or monolayer MXenes [4, 28]. In other words, HF etching should be used first before sonication. If other auxiliary ions or molecules, such as alkali, halide, dimethyl sulfoxide, hydrazine, urea, etc, are added during sonication treatment, the effect is similar to that of HF-containing etching and HF-forming etching [40–42]. Some of these ions and molecules can act as pillars to expand and maintain the interlayer spacing of MXenes, thereby improving their performance. Simon reported that intercalating surfactants into MXene layers could obtain MXenes with controlled interlayer spacing, which was beneficial for enhancing their electrochemical performance [43]. It is worth mentioning that the pillars in MXenes must be able to withstand their complex environment.

Although HF-containing etching and HF-forming etching reduce the harm of HF, researchers still hope to develop more environmentally friendly methods. In recent years, chemical vapor deposition technology has also been applied to the synthesis of MXene materials, and has become a promising method, because it can well control the thickness of the material [30, 44]. Besides, in order to reduce the adverse effects of some surface functional groups on the electrochemical performance of MXenes, some effective methods have also been explored. For example, OH functional groups can be converted to O terminal through high-temperature post treatment, whereby MXenes achieve better electrochemical storage performance [45]. For the same purpose, Sun et al successfully synthesized Ti$_2$CT$_x$ MXene by electrochemically etching Ti$_2$AlC in dilute hydrochloric acid solution [46]. Similarly, in 2018, Yang et al discovered that fluorine-free Ti$_3$C$_2$ MXene can also be prepared by electrochemical etching [36]. The schematic diagram of the specific preparation process is shown in figure 2(c). In this method, Cl took the place of F, and NH$_2$OH was added to assist in expanding the space between the layers during the stripping process. The experimental characterization showed that most of the obtained MXene nanosheets were single layer or double layer and had larger lateral size of over 2 µm. Based on electrochemical etching, Pang et al combined thermal-assisted technology and Ti$_2$CT$_x$, Cr$_2$CT$_x$ and V$_2$CT$_x$ MXene were also successfully prepared [47].

In addition to the methods and strategies mentioned above, molten salt, salt templated and alkali-assisted hydrothermal methods are able to be used to prepare fluorine-free MXenes as well [4, 28, 48, 49]. In recent years, in order to prepare fluorine-free MXenes, Lewis acid etching has been considered as a feasible method. In 2019, Mian Li et al developed a method to prepare Cl-terminated MXenes using traditional Al-containing MAX (Ti$_3$AlC$_2$, Ti$_2$AlC, Ti$_3$AlN and V$_2$AlC) as the precursor [50]. Typically, ZnCl$_2$ was used as a Lewis acid etchant to mix with the aluminum-containing MAX. Then, the mixture was heat-treated at 550 °C for 5 h under the protection of argon to convert the Al-containing MAX into the corresponding MXenes. It is worth
noting that the content of ZnCl₂ must be greatly excessive (MAX:ZnCl₂ = 1:6), because when the content of ZnCl₂ was relatively low (MAX:ZnCl₂ = 1:1.5), another type of MAX whose A element is Zn would be obtained. More recently, Youbing Li et al also proposed a new Lewis acid etching method to convert various traditional (Al-containing) and non-traditional (Si, Zn, Ga-containing) MAX phases into corresponding MXenes [49]. In a typical process, CuCl₂ molten salt was used as an etchant and Ti₃SiC₂ was used as a precursor. At a high temperature of 750 °C, the following reactions occurred:

$$\text{Ti}_3\text{SiC}_2 + 2\text{CuCl}_2 \rightarrow \text{Ti}_3\text{C}_2 + \text{SiCl}_4 (g) \uparrow + 2\text{Cu}$$

$$\text{Ti}_3\text{C}_2 + \text{CuCl}_2 \rightarrow \text{Ti}_3\text{C}_2\text{Cl}_4 + \text{Cu}$$

In order to remove the as-generated Cu particles, the product was then treated with (NH₄)₂S₂O₇ solution. This process introduced oxygen-containing groups, so the Tₓ in the final Ti₃C₂Tₓ MXene mainly included O terminated groups and Cl terminated groups. Furthermore, the authors proved that MXenes prepared by this method have the potential to become negative electrode materials with high rate performance. Impressively and inspiring, recently, Talapin et al successfully synthesized bare MXenes and MXenes with the desired terminal groups by treating MXenes with molten inorganic salts [51]. During this process, substitution and elimination reactions took place resulting in expected products. O, NH, S, Cl, Se, and Te-terminated MXenes have been produced by this method. Undoubtedly, these bare MXenes and MXenes terminated with specific functional groups will have a great impact on the application of MXenes in various fields. This method is a milestone breakthrough in the development of MXenes’ preparation technology. In short, although many vital breakthroughs have been made, the preparation technology of MXenes still needs to be continuously improved.

3. MXene-based materials for next-generation rechargeable batteries

3.1. Application of MXenes in alkali metal-ion batteries

SIBs and PIBs are very promising candidates for large-scale energy storage devices because of their low cost and similar working principle to LIBs. However, the larger radii of Na⁺ and K⁺ compared to Li⁺ require electrode materials to have large storage space so that finding applicable electrode materials becomes one of the biggest challenges for the successful commercialization of SIBs and PIBs. 2D MXenes have large interlayer distances and tremendous specific surface areas, which are conducive to the adsorption and insertion of ions with a larger radius. Thus, they are considered to be promising electrode materials for alkali metal-ion batteries. In theoretical studies, the calculated capacities of sodium on Ti₃C₂, V₂C and ZrₓN are 351.8, 606.42 and 545.9 mAh g⁻¹, respectively, and the diffusion barriers of sodium on these materials are very low, indicating that MXenes is a kind of material with good sodium storage performance [15, 17, 52]. In 2017, Lian et al used aqueous KOH solution to treat Ti₃C₂ to obtain alkali a-Ti₃C₂ nanoribbons and applied them to SIBs [53]. Due to the narrow width of the nanoribbons, the 3D interconnected porous network and the enlarged interlayer spacing derived from alkalinization, the materials exhibited good stability characterized by retaining about 50 mAh g⁻¹ after 500 cycles at 200 mA g⁻¹. It can be seen that the sodium storage capacity of a-Ti₃C₂ has a large gap compared with the theoretical capacity and it is insufficient to meet the actual use. As known, the surface of MXene materials inevitably carries functional groups and are usually negatively charged, enabling them to easily be combined with certain materials. This property is often used to construct MXene-based composite materials to increase their sodium storage capacity. Recently, Jiang’s team built MoSe₂/MXene heterojunction, where MXene is derived from Ti₃AlC₂, and used it as an electrode material of SIBs [54]. The morphology of MoSe₂/MXene can be observed in figure 3(a). The synergy between MoSe₂ and MXene was beneficial to obtain high capacity, fast electron and ion transport dynamics. In addition, according to the author’s description, the van der Waals force between MoSe₂ and MXene facilitated the structural stability of the heterojunction. Therefore, MoSe₂/MXene heterojunction exhibited excellent rate performance (490 mAh g⁻¹ at 1 A g⁻¹; 250 mAh g⁻¹ at 10 A g⁻¹, figure 3(b)) and outstanding cycling performance (retained 384 mAh g⁻¹ after 400 cycles at 2 A g⁻¹). Unlike sodium, the theoretical potassium storage capacity of MXenes is low, which can be ascribed to the larger radius of potassium. Therefore, as electrode materials for PIBs, MXenes need to be compounded with other materials [15–17]. Due to the similarity between PIBs and SIBs, the synthesis strategies of many electrode materials are also analogical. Huang et al used MoSe₂, MXene and carbon to form a ternary composite MoSe₂/MXene@C and applied it in PIBs [55]. The actual appearance of MoSe₂/MXene@C is shown in figure 3(c), similar to that of MoSe₂/MXene in figure 3(a). The composite also exhibited excellent rate performance with 183 mAh g⁻¹ at 10.0 A g⁻¹ (figure 3(d)). Both MoSe₂/MXene@C and MoSe₂/MXene have remarkable rate performance, proving that similar structures are relatively stable. In addition to the work mentioned above, SnS₂, MoS₂, graphene, porous carbon and other materials have also been used in combination with MXene and all have
achieved improved performance [35, 56–58]. From the perspective of development trends, well-designed structure combined with building composite is the mainstream to improve the electrochemical performance of MXenes.

3.2. Application of MXenes in ZIBs
In recent years, ZIBs, which generally use metallic zinc as the anode, have attracted wide attention due to their high specific capacity, abundant resources, and low cost [59–61]. Although the radius of Zn$^{2+}$ (0.74 Å) is smaller than that of Li$^+$ (0.76 Å), the larger mass of Zn$^{2+}$ and higher charge density hinder their migration in solid electrodes [60]. Therefore, the main dilemma currently encountered by ZIBs is to explore suitable cathode materials. According to theoretical simulations, many metal ions can migrate relatively quickly on MXenes. By analogy, if MXene materials are applied to ZIBs, their rate performance will benefit significantly. Venkatkarthick et al reported a composite material marked V$_2$O$_x$@V$_2$CT$_x$ for aqueous ZIBs and the battery configuration is shown in figure 4(a) [61]. The composite represented the vanadium-based oxides grown on the 2D V$_2$CT$_x$ MXene. Vanadium-based oxides can be formed by high-temperature etching methods or during electrochemical cycling. Under the synergistic effect of vanadium-based oxides and V$_2$CT$_x$ MXene, V$_2$O$_x$@V$_2$CT$_x$ exhibited ideal rate performance with a capacity of 304 mAh g$^{-1}$ at 0.05 A g$^{-1}$ and 84 mAh g$^{-1}$ at 2 A g$^{-1}$ and obvious plateaus could be seen on the potential–capacity curves even at current densities up to 1 and 2 A g$^{-1}$ (figure 4(b)). It can be seen from the work of Venkatkarthick et al that MXene will undergo phase transition behavior during electrochemical cycles and its derivatives also have the ability to store zinc. Recently, Li et al also paid close attention to V$_2$CT$_x$ MXene and applied it to aqueous zinc hybrid-ion batteries (ZHIBs) [59]. Surprisingly, the material exhibited superior cycling performance, as evidenced by it retaining high capacity after 18 000 cycles. What was even more unexpected was that during the 18 000 cycles, the overall capacity showed an upward trend (figure 4(c)). It was speculated that during the cycle process, V$_2$CT$_x$ MXene was converted into vanadium-based oxides which could store more zinc ions. To prove this conjecture, the authors used XRD for characterization. It could be clearly seen from figures 4(d)–(f) that in the first cycle, only V$_2$CT$_x$ existed in the cathode electrode, and as the number of cycles increased to three, the characteristic peak of V$_2$O$_3$ appeared in the XRD graph. After over 1000 cycles, the peak of V$_2$CT$_x$ weakened to become almost unclear, while that of V$_2$O$_3$ obviously increased. The above
works simultaneously used pristine MXenes and their derivatives as ion host materials, providing novel ideas for obtaining good-performance batteries with high rate and long cycling life.

In many ZIBs configurations, Zn foil is used directly as the anode. In fact, it is difficult to avoid the generation of dendrites in the Zn anode, which is also a safety risk for ZIBs. In order to weaken the adverse effects of Zn dendrites, various strategies have been designed, including designing a new type of separator, confecting a new type of electrolyte system, designing a favorable structure and performing interfacial modification. In terms of designing favorable structures, MXene materials have also demonstrated their unique contributions in recent years [62]. In 2019, Tian et al deposited Zn on Ti$_3$C$_2$T$_x$ MXene paper by electrodeposition to construct a flexible and free-standing Ti$_3$C$_2$T$_x$ MXene@Zn anode [63]. As a result, it was found that this anode had a good ability to inhibit the growth of Zn dendrites and also improved the Zn plating/stripping kinetics at the same time. In 2020, Zhang et al also applied MXene to construct a
Figure 5. (a) Schematic illustration of MIBs using 3D porous MXene film as the cathode; (b) digital image of 3D porous Ti$_3$C$_2$T$_x$ film; (c) second-cycle charge–discharge profile of the MIB using 3D porous MXene film as the cathode at 0.5 C. 1, 2 and 3 represent samples at different charge–discharge states. Inset sketch illustrates RMgCl intercalates the layer structure of Ti$_3$C$_2$T$_x$ MXene. Reprinted with permission from [66]. Copyright (2019) American Chemical Society. (d) Schematic diagram of the structure and preparation process of Ti$_3$C$_2$T$_x$@C complex, where CTAB refers to cetyltrimethylammonium bromide; (e) SEM image of Ti$_3$C$_2$T$_x$@C complex; (f) comparison of rate performance of Ti$_3$C$_2$T$_x$@C complex and Ti$_3$C$_2$T$_x$ MXene; (g) comparison of cycling performance of Ti$_3$C$_2$T$_x$@C complex and Ti$_3$C$_2$T$_x$ MXene. Reproduced from [67] with permission of The Royal Society of Chemistry.

dendrite-free Zn anode [64]. The method they used was to directly self-assemble MXene on the Zn anode. The prepared optimized Zn anode showed a cycle stability of 800 h at 0.2 mA cm$^{-2}$.

3.3. Application of MXenes in MIBs

Like zinc ions, magnesium ions are positive divalent ions, which gives them a greater interaction force with the host material, resulting in slower migration dynamics of magnesium ions [65]. However, due to its low price, abundant resources and high safety, MIBs have still won the favor of researchers. At present, researches on MIBs are still in the early stages of exploration. In order to improve the practicality of MIBs, one of the key challenges is to improve their dynamics. According to the facts indicated by theoretical simulations and calculations, some MXenes have good electrical conductivity and high magnesium storage capacity, so MXenes are expected to promote the breakthrough in the development bottleneck of MIBs [16]. In order to reduce the stacking and agglomeration of MXene nanosheets and facilitate the transport of ions, Barsoum and Gogotsi’s group constructed freestanding and flexible 3D macroporous Ti$_3$C$_2$T$_x$ film as the cathode electrode of MIBs [66]. Figures 5(a) and (b), respectively, show a schematic diagram of the corresponding MIB and a digital image of the prepared 3D macroporous Ti$_3$C$_2$T$_x$ film. Before assembling the battery, they used pre-incorporation technology to make magnesium ions enter Ti$_3$C$_2$T$_x$ film in advance to obtain a higher initial capacity. In terms of electrochemical performance, a 3D Mg$_{0.21}$Ti$_3$C$_2$T$_x$ MXene electrode delivered capacity of approximately 210, 140 and 55 mAh g$^{-1}$ at 0.5, 1.0 and 5.0 C, respectively, which is superior to many reported cathode materials of MIBs. In addition, the storage mechanisms of magnesium
ions on Ti$_3$C$_2$T$_x$ MXene were also studied, including the intercalation mechanism and redox reaction mechanism. The intercalation mechanism contributed most of the reversible capacity, while the redox reaction resulted in large irreversible capacity. Figure 5(c) shows the second-cycle charge–discharge profile of the MIB using 3D porous MXene film as the cathode at 0.5 C, and distinct plateaus, where often reflected intercalation reaction could be observed. The capacity decay caused the magnesium storage capacity of MXenes to be much lower than the theoretical capacity. Therefore, in follow-up research, some contributing measures should be taken to reduce the loss of irreversible capacity. In order to improve the cycle lifetime and magnesium storage capacity of the electrode, Liu et al. combined the negatively charged MXene and positively charged carbon nanospheres as a Ti$_3$C$_2$T$_x$@C cathode of MIBs using the principle of electrostatic adsorption [67]. The specific operation process and the structure of the expected Ti$_3$C$_2$T$_x$@C composite are shown in figure 5(d). The structure of the actual material obtained can be seen from the SEM image (figure 5(e)), indicating that using this method has achieved the expected effect. This method effectively increased the interlayer distance of MXene and prevented the MXene nanosheets from being re-stacked, which contributes to electrolyte infiltration and ion transmission. Electrochemical performance test results showed that the electrode had remarkable rate performance and outstanding cycle stability with about 85% capacity retention after 400 cycles (figures 5(f) and (g)). Furthermore, the authors mentioned that this method could also be applied to other MXene materials. In addition, inserting cationic surfactants or K$^+$ into MXenes can also increase the magnesium storage capability of MXenes [68, 69]. Moreover, in order to mitigate the inherent disadvantages of MIBs, applying MXenes to hybrid Mg$_2^+/Li^+$ batteries can also achieve impressive electrochemical performance [70, 71]. In order to improve the performance of MIBs, more types of materials and numerous novel electrode preparation methods need to be explored.

3.4. Application of MXenes in AIBs

Since ionic liquids have been used as electrolytes for AIBs, AIBs have attracted increasing attention in consideration of the abundant and cheap aluminum resources and high theoretical specific capacity of aluminum metal [72–74]. It is reasonable to imagine that an aluminum ion can exchange three electrons during a charge/discharge process, so an Al anode has a high specific capacity. However, similar to magnesium ions, aluminum ions have a higher charge density, and their interaction with host materials is more intense, resulting in sluggish kinetics [75]. Therefore, the preparation of suitable cathode materials is one of the key factors to promote the boom in AIBs. It is well known that MXenes are famous for their excellent electronic and ion conductive properties and theoretical studies have shown that both oxygen-terminated MXenes and bare MXenes have high aluminum storage capacity, so MXenes have also been studied as cathode materials for AIBs. In 2017, Mohammad et al. applied 2D V$_2$CT$_x$ MXene to AIBs [75]. They found that in the XRD pattern, there was no obvious change in the characteristic peaks before and after the charge and discharge processes, so they suggested that the charge storage mechanism of V$_2$CT$_x$ MXene was the reversible intercalation of aluminum ions. In addition, they proposed the reaction equation for the cathode reaction:

$$4\text{Al}^{3+} + 7\text{AlCl}_4^- \rightleftharpoons \text{Al}_4\text{Cl}_7^-$$

$$\text{V}_2\text{CT}_x + y\text{Al}^{3+} + 3y\text{e}^- \rightleftharpoons \text{V}_2\text{Al}_y\text{CT}_x$$

anode reaction:

$$\text{Al} + 7\text{AlCl}_4^- \rightleftharpoons 4\text{Al}_2\text{Cl}_7^- + 3\text{e}^-$$

Based on the speculated mechanism, they built a model of the charge–discharge mechanism of AIBs in which AlCl$_3$/[EMIm][Cl] ionic liquid was used as the electrolyte (figure 6(a)). Moreover, they also found that the conversion of multiple-layer MXene into few-layer MXene is capable of obtaining better electrochemical performance, which is consistent with the results of MXenes studied in other fields of electrochemical energy storage. The V$_2$CT$_x$ MXene with few layers exhibited a discharge capacity exceeding 300 mAh g$^{-1}$ at a current density of 100 mA g$^{-1}$. The research of Mohammad et al. laid a good foundation for MXenes to further expand the research in the field of AIBs. Recently, Li et al. studied the application of Ti$_3$C$_2$T$_x$ MXene in AIBs [76]. The electrochemical performance of unmodified Ti$_3$C$_2$T$_x$ is not ideal, so they mainly focused on building high-performance composite materials. After synthesizing Ti$_3$C$_2$T$_x$, dimethylsulfoxide (DMSO) was inserted between Ti$_3$C$_2$T$_x$ sheets. After DMSO treatment, the layer spacing of Ti$_3$C$_2$T$_x$ was expanded from about 0.98 to about 1.29 nm. Subsequently, they were oxidized at 200 °C and vulcanized at 600 °C, respectively, and finally the D-Ti$_3$C$_2$T$_x$@SS@TiO$_2$ composite was obtained. The specific preparation process is shown in figure 6(b). The introduction of elemental sulfur can react with the exposed Ti ions to form Ti–S bonds, evidenced by x-ray photoelectron spectroscopy (XPS) (figure 6(c)). The formation of Ti–S bonds is...
beneficial to maintain the original structure of the material and prevent MXene layers from restacking. Furthermore, the in situ growth of TiO$_2$ nanoparticles on MXene also facilitated improvement in the stability of the composite. As a result, the composite delivered a discharge capacity of 151.3 mAh g$^{-1}$ after 120 cycles, which is far better than the electrochemical performance of unmodified Ti$_3$C$_2$Tx (figure 6(d)). Impressively, a novel MXene labeled as Fe$_2$CS$_2$ has recently been proposed that it has good aluminum storage performance [26]. It can be seen from the formula that the MXene is different to ordinary MXenes and its surface functional groups are replaced by sulfur. The calculation results showed that, compared with Ti$_2$CO$_2$, the aluminum storage capacity of Fe$_2$CS$_2$ and the diffusion coefficient of aluminum ions in Fe$_2$CS$_2$ increased by orders of magnitude, suggesting that Fe$_2$CS$_2$ is a promising cathode material for AIBs. This work opens another door for improving the electrochemical performance of MXene materials.

### 3.5. Application of MXenes in LMBs

The anode materials currently used in commercial LIBs are mainly carbon-based materials, but lithium metal is the most ideal anode material for lithium-based batteries, because it has a very low potential and a high specific capacity, which is conducive to producing lithium batteries with high-energy density and high operating voltage [77, 78]. The reason lithium metal cannot be applied to lithium-based batteries is the problem of unavoidable lithium dendrite growth and infinite volume change [19, 77, 78]. At present, there are two main directions for solving this problem. One is to optimize the electrolytes and the other is to modify the lithium-metal anode. MXene materials have also been selected to improve the performance of LMBs due to their unique structure and properties. On the one hand, in terms of electrolytes, Ti$_3$C$_2$Tx MXene has been introduced into nanocomposite polymer electrolytes (CPEs) for LMBs because of its good ionic conductivity. Pan et al uniformly dispersed a small amount of Ti$_3$C$_2$Tx in a poly(ethylene oxide)/Lithium bis(trifluoromethylsulphonyl)imide (LiTFSI) complex (PEO$_{30}$-LiTFSI) by a simple solution blending method to form MXene-based CPEs (MCPEs) [79]. The introduction of 2D MXene flakes to PEO was beneficial to hinder the crystallization of PEO and boost its segmental motion as well as improving the ionic conductivity of the electrolyte. The experimental results showed that an LMB using MCPE containing only 1.5 wt% MXene had rate capability and stability comparable to the latest CPELMB, indicating that MXene materials have great potential in improving the performance of electrolytes for LMBs. On the other hand, MXenes are more often used to improve the performance of lithium-metal anodes. For example, Wu et al designed a conductive and lithiophilic MXene/graphene framework to assist in the preparation of
high-capacity, dendrite-free lithium-metal anodes [77]. The electrode with a record lifetime of up to 2700 h was able to remain stable for 230 cycles at 20 mA cm$^{-2}$ which is a fairly high current density. Zhang et al prepared MXene aerogel as a high-performance scaffold for lithium-metal anodes [78]. According to the authors’ analysis, MXene aerogel had three main functions. First, the oxygen-rich functional groups on the MXene sheet had the ability to induce uniform nucleation of Li. Second, the cross-linked network of MXene sheets contributed a high-efficiency path to electron conduction and ion transportation, and is even conducive to the growth of Li as well. Third, the interconnected interspaces in the MXene aerogel were beneficial to buffer volume changes and achieve high lithium loading. The schematic diagram of the MXene scaffold and the plating/stripping process of Li in MXene aerogel scaffold are shown in figure 7(a). Due to the above advantages, the prepared electrode had prominent cycle stability and low over-potential as the current density reached 10 mA cm$^{-2}$. Obtaining high-performance lithium-metal anodes is inseparable from elaborate structural design. Recently, Yang et al developed a new type of perpendicular MXene-Li array with adjustable MXene walls and a constant space between them to serve as an anode for LMBs [19]. The regularly arranged vertical MXene array contains two periodic interspaces, one is a nanoscale interspace in MXene walls, which facilitates the rapid transfer of lithium ions during stripping and plating, and the other is a microscale interspace between the MXene walls, which effectively homogenize the electric field. Even more impressive is that in this vertical MXene array, the undesired lightning rod effect and volume change are effectively suppressed, thereby obtaining a dendrite-free lithium anode with high capacity and stable structure. Due to the ingenious arrangement structure, the cathode possessed a low potential of 25 mV and an ultrahigh capacity reaching 2056 mAh g$^{-1}$. As for its cycling performance, the authors compared the stability of reduced graphene oxide array, copper array and MXene array. The performance of MXene array was capable of cycling steadily up to 1700 h, far superior to that of the other two materials (figure 7(b)). The above examples highlight the important role of MXene in promoting the performance of LMBs. In further studies, due to the diversity of MXenes compositions and the differences in properties derived from different preparation methods, it is expected that reasonable utilization of MXenes can significantly improve the performance of LMBs.
3.6. Application of MXenes in LSBs

Compared with LMBs, LSBs use sulfur as the cathode material, which will undergo multi-electron reactions during charge/discharge processes. Thus, LSBs are well known for their high capacity and energy density, whereby they become a kind of very promising next-generation rechargeable battery [80]. However, several obstacles stagnate the development of LSBs. First, sulfur is an insulating material, having poor conductivity [81]. Second, during the charge and discharge process, sulfur may be converted into inactive by-products, causing the capacity to decrease quickly. Some by-products will dissolve in the electrolyte and react with lithium, thereby forming an undesirable insulating layer on the surface of the lithium anode, resulting in severe polarization [82]. Third, the large volume expansion (about 80%) caused by the conversion of S to Li2S is not conducive to retaining the stability of the electrode [80]. In recent years, MXene materials have been used to break through the shortcomings of LSBs due to their special conductivity, good mechanical properties and affinity. In a previous discussion, MXene nanoribbons were applied to PIBs and SIBs, proving that the construction of nanoribbons is an effective way to improve the electrochemical performance of MXenes. In 2018, Ti3C2 nanoribbons were also used as a host material for sulfur by Dong et al [80]. In addition, they applied Ti3C2 nanosheets to the polypropylene separator as an interlayer by way of filtration to suppress the shuttle effect of lithium polysulfide. So a-Ti3C2-S/d-Ti3C2/PP electrode was prepared and the fabrication process is shown in figure 8(a). As a consequence, desirable electrochemical performance was achieved. Heteroatom doping has proved to be another way to improve the electrochemical performance of MXenes and this method has also been applied to LSBs [83]. Bao et al prepared nitrogen-doped MXene nanosheets with a crumpled morphology as a host material for sulfur through a simple annealing process [81]. Their experimental results showed that the nitrogen-doped MXene nanosheets had strong physical and chemical adsorption capabilities, which were favorable for the effective absorption of polysulfides and could obtain a high areal sulfur loading of 5.1 mg cm⁻². The appearance of the crumpled nitrogen-doped Ti3C2Tx/sulfur composites (crumpled N–Ti3C2Tx/S) and the site of nitrogen doping as well as the location of sulfur attachment are simulated in figure 8(b). Furthermore, crumpled N–Ti3C2Tx/S exhibited quite satisfactory electrochemical performance with a high reversible capacity of 1144 mAh g⁻¹ at a rate of 0.2 C and 610 mAh g⁻¹ after 100 cycles at 2 C (figure 8(c)). This preparation method is most suitable due to its simplicity and efficiency. Generally speaking, no material is perfect, but studies have shown that conductive carbon materials, some metal oxides/nitride/sulfides and organic framework materials can also alleviate some of the difficulties faced by LSBs to some extent [84]. Therefore, the combination of MXene materials with carbon materials, MoS2 or other materials as host materials for sulfur has also been reported, and all have a positive effect on the electrochemical performance of LSBs [82, 85]. Hence, combining the advantages of various favorable materials is also an important way to improve the performance of LSBs.

3.7. Application of MXenes in LOBs

LOBs, sometimes called Li–air batteries, have attracted great attention due to their ultra-high specific energy density and are especially suitable for electronic equipment that requires long-distance transportation [86]. A typical LOB usually uses Li metal as the active material of the negative electrode, O2 in the air as the active substance of the positive electrode and an electrolyte containing Li [87]. Although some progress has been made, LOBs still face many difficult problems. Regardless of the problem of lithium dendrites that are generated in general in lithium metal-based batteries, the sluggish cathodic reactions (oxygen reduction reaction and oxygen evolution reaction) are the key to restricting the development of LOBs [88]. Therefore, designing an efficient and durable cathode catalytic system is the key to improving the rate performance and cycle life of LOBs. Carbon materials are widely used as cathode materials for LOBs due to their large specific surface area, low cost, good electrical conductivity and suitable pore structure. However, in the LOB system, carbon will be corroded and other side reactions will occur, which will reduce the efficiency of the cathodic reaction and working life of the battery [89]. In recent years, MXenes have been considered as a promising cathode material for LOBs due to its stable structure, excellent conductivity of electrons/ions and extraordinarily high surface coverage [86, 90]. Many coordination catalytic systems combining high-efficiency catalysts and MXene have been developed and applied to LOBs. Zheng et al used the ethanol-thermal method to in situ grow oxygen vacancy-rich TiO2 nanoparticles with high-efficiency catalytic properties on Ti3C2Tx nanosheets, thereby constructing a V-TiO2/Ti3C2Tx composite as the oxygen electrode of LOBs (figure 9(a)) [91]. This catalytic system had the following advantages. First, small and uniformly fixed TiO2 nanoparticles on multilayer MXene nanosheets greatly improved the stability and availability of the active materials. Second, MXene can stabilize oxygen vacancies, which acted as active sites for catalyzing cathodic reactions and contributed to improving the migration rate of electrons and Li⁺. Third, the multilayer structure of this composite facilitated the penetration of the electrolyte and mitigated the volume variation of the electrode caused by the deposition and decomposition of Li2O2. As a result, the LOB using V-TiO2/Ti3C2Tx composite as cathode material exhibited improved performance with high
discharge specific capacity of 11487 at 100 mA g\(^{-1}\) and low overpotential (0.21 V). In terms of cycle performance, 79% round-trip efficiency can still be maintained after 200 cycles (figure 9(b)). Furthermore, V-TiO\(_2\)/Ti\(_3\)C\(_2\)T\(_x\), NiO/Ti\(_3\)C\(_2\) [92], LaSrCoO/Ti\(_3\)C\(_2\)T\(_x\) [93], CoO/Ti\(_3\)C\(_2\)T\(_x\) [94] and many other catalytic systems have also achieved remarkable performance. Nonetheless, LOBs still need more progress.

3.8. Application of MXenes in SMBs and PMBs

Similar to Li, Na metal and K metal are also regarded as ideal anode materials with high capacity and low potential. However, the same problem of uneven dendritic growth also hinders the application of Na metal and K metal [95]. Therefore, finding a host material that is capable of inducing or suppressing the growth of
Na/K dendrites is the key to enabling the large-scale application of SMBs and PMBs. In view of the positive role of MXenes in inhibiting the growth of lithium dendrites, MXenes have also been applied to design ultra-stable Na metal anodes and K metal anodes.

Recently, Li et al constructed a MXene-derived 1D/2D Na$_3$Ti$_5$O$_{12}$-MXene hybrid architecture (C-NTO) as a host material for Na by simply pretreating Ti$_3$C$_2$ with CTAB and then oxidizing it with NaOH (figure 10(a)) [96]. After these two steps, 1D Na$_3$Ti$_5$O$_{12}$ nanowires were grown between 2D MXene nanosheets. The SEM image of C-NTO is shown in figure 10(b). Because the 1D Na$_3$Ti$_5$O$_{12}$ nanowires with the effect of inducing Na nucleation provided a large number of nucleation sites, coupled with the confinement effect of 2D MXene, this hybrid structure effectively restrained the growth of Na dendrites, making it possible to achieve cycling for 200 cycles steadily at a high current density of 10 mA cm$^{-2}$ (figure 10(c)).

Previous studies have shown that alkalization can convert MXenes into 3D nanoribbons and the products have been applied to PIBs, SIBs and LSBs. Recently, similar work by Shi et al showed that the alkalized Ti$_3$C$_2$ (a-Ti$_3$C$_2$) framework was also able to be used as a substrate for K deposition, thereby constructing a
dendritic-free K metal anode (figure 10(d)) [97]. The practical morphology of the a-Ti$_3$C$_2$ framework had been revealed by SEM image (figure 10(e)). Electrochemical tests revealed that under a plating capacity of 5 mAh cm$^{-2}$, the a-Ti$_3$C$_2$ based anode had the ability to cycle stably for 800 h with a small overpotential (18 mV) (figure 10(f)).

Impressively, not long ago, Shi et al also designed a 3D conductive Ti$_3$C$_2$T$_x$ MXene–melamine foam (MXene–MF) which was suitable to be used as a universal host material for Na, K and Li [98]. These works strongly proved the effectiveness of MXenes in inhibiting the growth of metal dendrites.

4. Summary and outlook

In this cutting-edge review, we briefly summarize the properties and synthesis methods of MXenes and their current research progress. Subsequently, we mainly focus on the application status of MXenes in a series of batteries including PIBs, SIBs, ZIBs, AlIBs, LMBs, LSBs, LOBs, SMBs and PMBs. Furthermore, MXenes also have considerable calcium storage capacity in theoretical researches, so they are also expected to be widely used in CIBs in the future [16, 17]. Judging from the application of MXenes in the various above-mentioned batteries, they have been widely used in various fields concerning energy storage and conversion, demonstrating their tremendous potential for commercial application. However, in view of their present situation, MXenes-based materials still face some problems and challenges that need to be resolved. In order to further improve their performance and increase the possibility of their commercial application, the following points need to be considered in future researches:

(a) Consideration from the aspect of the synthesis method. Different MXenes have different composition elements, so their suitable synthesis methods are different. Even for MXenes with the same chemical formula, due to the different etching methods selected, their respective properties may also be discrepant, because the preparation methods have a great impact on their morphology and surface functional groups. Therefore, choosing a reasonable preparation method is the key factor to obtain MXenes with high performance. Quite a few studies have shown that many cations or molecules can intercalate into the interspaces of MXenes, achieving the purpose of expanding the layer spacing, which is beneficial to obtain delaminated MXenes or improve their electrochemical performance. However, attention should be paid to the selection of intercalation materials and solvents at this time to avoid introducing unwanted groups. Moreover, the results of theoretical studies indicate that bare MXenes may have better electronic conductivity, ionic conductivity and capacity to adsorb ions. In addition, some surface functional groups are detrimental to the electrochemical performance of MXenes, so much effort should be made to develop MXenes with specific surface groups and bare MXenes. According to the current research results, MXenes containing F and Cl do not perform well when used as electrodes in metal-ion batteries. However, MXenes synthesized by most existing methods usually contain one of them. Therefore, it is expected that simple and effective methods should be investigated to obtain MXenes with the desired surface groups. It is worth noting that the etching methods concerning HF are considered to be environmentally hazardous and not safe. Thus, exploiting a fluorine-free etching method is also a development direction in the future. Inspiringly, recent progress of MXenes in the preparation method, such as Lewis acid etching and chemical vapor deposition, may promote the application of MXenes in the field of energy storage and conversion.

(b) Consideration from the perspective of modification methods. Based on the above discussions, it has been found that MXene nanoribbons have been used in SIBs, PIBs, LSBs and PMBs, and MXene aerogels have also been applied to LMBs, indicating that reasonable morphology control is beneficial to improve the electrochemical properties of MXene materials. In addition, heteroatom doping has proved to be an effective modification method. For example, nitrogen-doped MXene has been properly applied to LSBs. There are also related reports in the fields of LIBs [99, 100]. Based on this, we speculate that heteroatom doping could also improve the performance of MXenes in other ion batteries. There is no doubt that compounding with other materials is a direct and effective modification method, and the key lies in how to design well-knit composites with high performance. Because of its unique properties, MXenes have the ability to form a strong combination with many materials, so MXene-based composite materials will flourish and can be applied to various energy storage and conversion fields. In addition, under proper conditions, a MXene is prone to convert into another compound, which is usually also an active substance or can induce metal deposition. Therefore, the use of MXenes to prepare MXene-derived materials or hybrid materials is also an effective way to improve their performance. Meanwhile, by using this method, the structural advantages of MXenes can be retained.

(c) Considering its use. It can be found from the application of MXenes in the various above-mentioned batteries that the application form of MXenes is different, some as cathode materials, some as anode materials, some as a part of separators and some as a part of electrolytes. In particular, the role of MXenes
### Table 1. Application of MXenes in various post-lithium-ion batteries.

| Materials                  | Rate performance | Cyclic performance | Ref. |
|----------------------------|------------------|--------------------|------|
| 2D MXene/SnS$_2$           | 901 mAh g$^{-1}$ at 50 mA g$^{-1}$; 78 mAh g$^{-1}$ at 2000 mA g$^{-1}$ | 120 mAh g$^{-1}$ after 125 cycles under 0.5 C at 50 mA g$^{-1}$ | [56] |
| VO$_2$/MXene               | 323 mAh g$^{-1}$ at 50 mA g$^{-1}$; 206 mAh g$^{-1}$ at 1600 mA g$^{-1}$ | 141% after 200 cycles at 0.1 A g$^{-1}$ | [101] |
| Ti$_3$C$_2$/NiCoP          | 416.9 mAh g$^{-1}$ at 100 mA g$^{-1}$; 240.1 mAh g$^{-1}$ at 2 A g$^{-1}$ | 261.7 mAh g$^{-1}$ after 2000 cycles at 1 A g$^{-1}$ | [102] |
| a-Ti$_3$C$_2$              | 168 mAh g$^{-1}$ at 20 mA g$^{-1}$; 84 mAh g$^{-1}$ at 200 mA g$^{-1}$ | ~50 mAh g$^{-1}$ after 500 cycles at 1 A g$^{-1}$ | [53] |
| f-Ti$_3$C$_2$/T$_x$ _DMSO_ | 110 mAh g$^{-1}$ at 2 A g$^{-1}$ | 76 mAh g$^{-1}$ after 1500 cycles at 1 A g$^{-1}$ | [103] |
| 3D V$_2$CT$_x$             | 170 mAh g$^{-1}$ at 25 C | 310 mAh g$^{-1}$ after 1000 cycles at 2.5 C | (1 C = 200 mAh g$^{-1}$) | [104] |
| sulfur-decorated Ti$_3$C$_2$ | 210.6 mAh g$^{-1}$ at 0.4 A g$^{-1}$; 135 mAh g$^{-1}$ after 1000 cycles at 2 A g$^{-1}$ | 189 mAh g$^{-1}$ after 1000 cycles at 1 A g$^{-1}$ | [105] |
| c-Ti$_3$C$_2$T$_x$         | 420 mAh g$^{-1}$ at 50 mA g$^{-1}$; 295 mAh g$^{-1}$ at 2 A g$^{-1}$ | 472 mAh g$^{-1}$ after 100 cycles at 100 mA g$^{-1}$ | [106] |
| PDMAA-BP/Ti$_3$C$_2$       | 1773 mAh g$^{-1}$ at 0.1 A g$^{-1}$; 461 mAh g$^{-1}$ at 2 A g$^{-1}$ | 658 mAh g$^{-1}$ after 2000 cycles at 1 A g$^{-1}$ | [107] |
| p-Ti$_3$C$_2$T$_x$         | 166 mAh g$^{-1}$ at 1 A g$^{-1}$; 124 mAh g$^{-1}$ at 10 A g$^{-1}$ | 189 mAh g$^{-1}$ after 1000 cycles at 1 A g$^{-1}$ | [108] |
| Sn$_2$O$_3$/Ti$_3$C$_2$T$_x$ | 422 mAh g$^{-1}$ at 0.5 A g$^{-1}$; 295 mAh g$^{-1}$ at 2 A g$^{-1}$ | 472 mAh g$^{-1}$ after 100 cycles at 100 mA g$^{-1}$ | [109] |
| Bi$_2$S$_3$/MXene          | 407 mAh g$^{-1}$ at 0.1 A g$^{-1}$; 168 mAh g$^{-1}$ at 5 A g$^{-1}$ | 155 mAh g$^{-1}$ after 250 cycles at 500 mA g$^{-1}$ | [110] |
| NaTi$_2$3O$_6$             | 196 mAh g$^{-1}$ at 50 mA g$^{-1}$; 101 mAh g$^{-1}$ at 2 A g$^{-1}$ | ~130 mAh g$^{-1}$ after 150 cycles at 200 mA g$^{-1}$ | [111] |
| Ti$_3$CN                   | 183.8 mAh g$^{-1}$ at 20 mA g$^{-1}$; 98.8 mAh g$^{-1}$ at 500 mA g$^{-1}$ | 60 mAh g$^{-1}$ after 500 cycles at 500 mA g$^{-1}$ | [112] |
| MoSe$_2$/MXene             | 559 mAh g$^{-1}$ at 0.5 A g$^{-1}$; 250 mAh g$^{-1}$ at 10 A g$^{-1}$ | 384 mAh g$^{-1}$ after 400 cycles at 2 A g$^{-1}$ | [54] |
| Freestanding-rGpTiC         | 280 mAh g$^{-1}$ at 100 mA g$^{-1}$ | 84.8% after 1000 cycles at 1 A g$^{-1}$ | [113] |
| PiB                        | a-Ti$_3$C$_2$     | 141 mAh g$^{-1}$ at 0.2 A g$^{-1}$; 60 mAh g$^{-1}$ at 0.3 A g$^{-1}$ | ~42 mAh g$^{-1}$ after 500 cycles at 0.2 A g$^{-1}$ | [53] |
| Ti$_3$CNT$_x$              | 254.8 mAh g$^{-1}$ at 1 A g$^{-1}$; 183 mAh g$^{-1}$ at 10 A g$^{-1}$ | 252.2 mAh g$^{-1}$ after 2000 cycles at 1 A g$^{-1}$ | [57] |
| PDMAA-NPCN/Ti$_3$C$_2$     | 499.8 mAh g$^{-1}$ at 0.1 A g$^{-1}$; 168.2 mAh g$^{-1}$ at 0.5 A g$^{-1}$ | 145.5 mAh g$^{-1}$ after 50 cycles at 0.2 A g$^{-1}$ | [35] |
| MXene/MoS$_2$              | 290.7 mAh g$^{-1}$ at 0.05 A g$^{-1}$; 183 mAh g$^{-1}$ at 10 A g$^{-1}$ | 317 mAh g$^{-1}$ after 300 cycles at 1 A g$^{-1}$ | [114] |
| MoSe$_2$/MXene@C           | 350 mAh g$^{-1}$ at 0.1 A g$^{-1}$; 183 mAh g$^{-1}$ at 10 A g$^{-1}$ | 79.1435% after 500 cycles at 0.5 A g$^{-1}$ | [115] |
| Ti$_3$C$_2$T$_x$@Sb        | 503.84 mAh g$^{-1}$ at 0.05 A g$^{-1}$; 270.81 mAh g$^{-1}$ at 0.5 A g$^{-1}$ | 311 mAh g$^{-1}$ after 300 cycles at 5 A g$^{-1}$ | [116] |
| K$_2$Ti$_3$O$_7$           | 105 mAh g$^{-1}$ at 0.1 A g$^{-1}$; 81 mAh g$^{-1}$ at 0.3 A g$^{-1}$ | ~45 mAh g$^{-1}$ after over 900 cycles at 1 A g$^{-1}$ | [111] |
| MXene-bonded HC            | 102.2 mAh g$^{-1}$ at 0.5 A g$^{-1}$; 81 mAh g$^{-1}$ at 0.3 A g$^{-1}$ | 210 mAh g$^{-1}$ after 100 cycles at 0.05 A g$^{-1}$ | [116] |
| BPE@V$_2$CT$_x$            | 593.6 mAh g$^{-1}$ at 0.1 A g$^{-1}$; 229.6 mAh g$^{-1}$ at 2 A g$^{-1}$ | 261 mAh g$^{-1}$ after 3000 cycles at 2 A g$^{-1}$ | [117] |
| NG/ReSe$_2$/MXene          | 395.3 mAh g$^{-1}$ at 0.1 A g$^{-1}$; 137.5 mAh g$^{-1}$ at 10 A g$^{-1}$ | 90 mAh g$^{-1}$ after 300 cycles at 5 A g$^{-1}$ | [118] |
| ZIB                        | DV$_2$C@CNT       | 190.2 F g$^{-1}$ at 0.5 A g$^{-1}$; 90.2 F g$^{-1}$ at 10 A g$^{-1}$ | over 4000 cycles at 0.5 A g$^{-1}$ | [119] |
| MZn-60                     | 48 mV at 0.5 mA cm$^{-2}$; 112 mV at 5 mA cm$^{-2}$ | 800 h at 0.2 mA cm$^{-2}$ | [64] |
| 3D-Nb$_2$CT$_3$, NW        | 350.9 mAh g$^{-1}$ at 0.2 A g$^{-1}$; 250.4 mAh g$^{-1}$ at 8 A g$^{-1}$ | ~100 mAh g$^{-1}$ after 150 cycles at 300 mA g$^{-1}$ | [120] |

(Continued.)
Table 1. (Continued.)

| Materials | Rate performance | Cyclic performance | Ref. |
|-----------|-----------------|-------------------|-----|
| V<sub>2</sub>CT<sub>x</sub> | 404.0 mAh g<sup>-1</sup> at 0.5 A g<sup>-1</sup>; 184.1 mAh g<sup>-1</sup> at 20 A g<sup>-1</sup> | 202 mAh g<sup>-1</sup> after 16 000 cycles at 1 C | [59] |
| V<sub>2</sub>O<sub>3</sub>@V<sub>2</sub>CT<sub>x</sub> | 224 mAh g<sup>-1</sup> at 0.1 A g<sup>-1</sup>; 84 mAh g<sup>-1</sup> at 2 A g<sup>-1</sup>; ~100 mAh g<sup>-1</sup> at 20 A g<sup>-1</sup> | 10 A g<sup>-1</sup>; ~87.7 mAh g<sup>-1</sup> after 200 cycles at 0.5 C | [61] |
| Ti<sub>3</sub>C<sub>2</sub>I<sub>2</sub> | 120 mAh g<sup>-1</sup> at 0.25 A g<sup>-1</sup>; ~67 mAh g<sup>-1</sup> at 15 A g<sup>-1</sup> | ~90 mAh g<sup>-1</sup> after 1000 cycles at 0.1 C | [27] |
| ZMO@Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> | 102.8 mAh g<sup>-1</sup> at 2 A g<sup>-1</sup>; 84.5 mAh g<sup>-1</sup> at 4 A g<sup>-1</sup> | 92.4% after 5000 cycles at 1 A g<sup>-1</sup> | [122] |
| V<sub>2</sub>AIC–V<sub>2</sub>CT<sub>x</sub>–V<sub>2</sub>O<sub>3</sub> | 97.5 mAh g<sup>-1</sup> at 64 A g<sup>-1</sup>; 397 mAh g<sup>-1</sup> at 0.5 A g<sup>-1</sup>; 290 mAh g<sup>-1</sup> at 4 A g<sup>-1</sup> | 4000 cycles at 5 A g<sup>-1</sup> | [50] |
| Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>, MXene@Zn MIBs | ~210 mAh g<sup>-1</sup> at 0.5 C; ~55 mAh g<sup>-1</sup> at 5 C | ~50 mAh g<sup>-1</sup> after 60 cycles at 1 C (1 C = 100 mA g<sup>-1</sup>) | [66] |
| Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/CTAB | 100 mAh g<sup>-1</sup> at 0.05 A g<sup>-1</sup>; 32 mAh g<sup>-1</sup> at 2 A g<sup>-1</sup> | 135 mAh cm<sup>-2</sup> after 250 cycles at 0.2 A cm<sup>-2</sup> | [68] |
| Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/C | 198.7 mAh g<sup>-1</sup> at 10 mAh g<sup>-1</sup>; 123.3 mAh g<sup>-1</sup> at 200 mAh g<sup>-1</sup> | 140.6 mAh g<sup>-1</sup> after 400 cycles at 50 mAh g<sup>-1</sup> | [67] |
| MnO<sub>2</sub>/MXene–Ti<sub>3</sub>C<sub>2</sub> | 54 mAh g<sup>-1</sup> at 100 mAh g<sup>-1</sup>; 21 mAh g<sup>-1</sup> at 500 mAh g<sup>-1</sup> | 58 mAh g<sup>-1</sup> after 100 cycles at 50 mAh g<sup>-1</sup> | [124] |
| MoS<sub>2</sub>/MXene | 165 mAh g<sup>-1</sup> at 50 mAh g<sup>-1</sup>; 93 mAh g<sup>-1</sup> at 200 mAh g<sup>-1</sup> | 108 mAh g<sup>-1</sup> after 50 cycles at 50 mAh g<sup>-1</sup> | [125] |
| d-Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>/CNT (hybrid Mg<sup>2+</sup>/Li<sup>+</sup> batteries) | 100 mAh g<sup>-1</sup> at 0.1 C; 50 mAh g<sup>-1</sup> at 5 C | 80 mAh g<sup>-1</sup> after 500 cycles at 1 C (1 C = 100 mA g<sup>-1</sup>) | [71] |

(Continued.)
| Materials                          | Rate performance                                      | Cyclic performance                              | Ref.   |
|-----------------------------------|-------------------------------------------------------|-------------------------------------------------|--------|
| Lithium-oxygen batteries          |                                                       |                                                 |        |
| Mo2CTx, MXene/CNT                 |                                                        | over 40 cycles at 200 mA g⁻¹                   | [90]   |
| CoO/Ti3C2Tx                      | 16 220 mA h g⁻¹ at 100 mA g⁻¹; 8560 mA h g⁻¹ at 500 mA g⁻¹ | over 160 cycles at 100 mA g⁻¹                   | [94]   |
| V-TiO2/Ti3C2Tx                   | 1.61 V at 800 mA g⁻¹                                   | 200 cycles at 100 mA g⁻¹—1000 mA g⁻¹          | [91]   |
| NiO/Ti3C2                        | 13 350 mA h g⁻¹ at 100 mA g⁻¹; 5790 mA h g⁻¹ at 500 mA g⁻¹ | over 90 cycles at 500 mA g⁻¹                   | [92]   |
| LuSrCoO/Ti3C2Tx                   | 1.29 V at 1000 mA g⁻¹                                  | over 80 cycles at 500 mA g⁻¹                   | [93]   |
| LSBs                              |                                                       |                                                 |        |
| MSC-2                             | 1031.2 mA h g⁻¹ at 0.1 C; 502.3 mA h g⁻¹ at 2 C        | 946.7 mA h g⁻¹ after 200 cycles at 0.1 C       | [134]  |
| Ti3CTx/S                          | 1383 mA h g⁻¹ at 0.1 C; 1075 mA h g⁻¹ at 2 C           | 970 mA h g⁻¹ after 1500 cycles at 1 C          | [135]  |
| Co-CNT@MXene/S                    | 1323.25 mA h g⁻¹ at 0.05 C; 789.29 mA h g⁻¹ at 0.5 C  | ∼600 mA h g⁻¹ after over 200 cycles at 0.5 C   | [136]  |
| a-Ti3CTx2−S/d-Ti3C2/PP            | 744 mA h g⁻¹ at 0.5 C; 288 mA h g⁻¹ at 10 C            | 50.4% after 200 cycles at 2 C                 | [80]   |
| S@N-PC/Ti3C2                     | 1107 mA h g⁻¹ at 0.1 C; 595 mA h g⁻¹ at 2 C            | 527 mA h g⁻¹ after 800 cycles at 1 C           | [137]  |
| Ti3C2T2x(4h)-GN                   | 663 mA h g⁻¹ at 2 C                                    | over 1000 cycles at 2 C                        | [138]  |
| S@SA-Zn-MXene                    | 517 mA h g⁻¹ at 6 C                                    | 706 mA h g⁻¹ after 400 cycles at 1 C           | [139]  |
| Ti3C2T2x/RGO/S                   | 1179 mA h g⁻¹ at 0.5 C; 750 mA h g⁻¹ at 5 C            | 878.4 mA h g⁻¹ after 300 cycles at 0.5 C       | [140]  |
| S@TiO2/Ti3C                      | 879.2 mA h g⁻¹ at 0.2 C; 317.7 mA h g⁻¹ at 5 C         | 464 mA h g⁻¹ after 200 cycles at 2 C           | [141]  |
| N-Ti3C2T2x/S                     | 947 mA h g⁻¹ at 0.5 C; 770 mA h g⁻¹ at 2 C             | 610 mA h g⁻¹ after 1000 cycles at 2 C          | [81]   |
| MPP separators                   | 1046.9 mA h g⁻¹ at 0.2 C; 743.7 mA h g⁻¹ at 1 C         | 550 mA h g⁻¹ after 500 cycles at 0.5 C          | [142]  |
| CMP separator                    | 1312 mA h g⁻¹ at 0.1 C; 728 mA h g⁻¹ at 2 C            | 614 mA h g⁻¹ after 600 cycles at 1 C           | [143]  |
| 50% S@Ti3C2T2x                   | 1350 mA h g⁻¹ at 0.1 C; 1161 mA h g⁻¹ at 2 C           | 1170 mA h g⁻¹ after 175 cycles at 2 C          | [144]  |
| N-Ti3C2/C@PP separator           | 1111 mA h g⁻¹ at 0.2 C; 675 mA h g⁻¹ at 2 C            | 716 mA h g⁻¹ after 500 cycles at 0.5 C          | [145]  |
| 79S/CNT-Ti3C2                    | 1216 mA h g⁻¹ at 1.5 mg cm⁻²; 910 mA h g⁻¹ at 5.5 mg cm⁻² | ∼450 mA h g⁻¹ after 1200 cycles at 0.5 C       | [82]   |
| MX-NF/PP                         | 1234 mA h g⁻¹ at 0.2 C; 794 mA h g⁻¹ at 3 C            | 645 mA h g⁻¹ after 1000 cycles at 1 C          | [146]  |
| S@V2C–Li/C                       | 1093 mA h g⁻¹ at 0.1 C; 400 mA h g⁻¹ at 5 C            | 600 mA h g⁻¹ after 500 cycles at 0.5 C          | [147]  |
| T@CP separator                   | 1110 mA h g⁻¹ at 0.5 C; 950 mA h g⁻¹ at 2.5 C          | ∼1100 mA h g⁻¹ after 200 cycles at 0.25 C      | [84]   |
| MXene/ESM separator              | 1321 mA h g⁻¹ at 0.1 C; 948 mA h g⁻¹ at 1 C            | ∼877 mA h g⁻¹ after 250 cycles at 0.5 C         | [148]  |
| MXene/1T-2H MoS2-C-S              | 1194.7 mA h g⁻¹ at 0.1 C; 677.2 mA h g⁻¹ at 2 C         | 799.3 mA h g⁻¹ after 300 cycles at 0.5 C        | [85]   |
| SMBs                             |                                                       |                                                 |        |
| h-Ti3C2/CNTs                     | 11 mV at 1 mA cm⁻²; 46 mA at 5 mA cm⁻²                 | over 4000 h at                                 | [149]  |
| Na-Ti3C2T2x−CC                   | ∼0.05 V at 0.5 mA cm⁻²; ∼0.35 V at 9 mA cm⁻²           | over 300 h at 3 mA cm⁻²—1.0 mA cm⁻²            | [150]  |
| CT-Sn[II]@Ti3C2                  | 40 mA at 4 mA cm⁻²                                    | over 500 cycles at 4 mA cm⁻²                   | [151]  |
| C-NT0-3/Na                        |                                                       | over 400 cycles at 3 mA cm⁻²                   | [96]   |
| MXene-MF-Na                      | ∼15 mA at 20 mA cm⁻²                                   | 3 mA cm⁻²                                      | [98]   |
| MBs                              |                                                       |                                                 |        |
| MXene-MF-K                       | 0.11 V at 0.1 mA cm⁻²; 0.40 V at 2 mA cm⁻²             | 800 h at 5 mA cm⁻²                              | [98]   |
| K@DN-MXene/CNT                   |                                                       | 300 h at 0.5 mA cm⁻²                           | [18]   |
| a-Ti3C2                           |                                                       | 700 h at 10 mA cm⁻²                             | [97]   |
in metal-ion batteries is different to that in LMBs and LSBs. In the former, MXenes are mainly used as electrode materials for storing ions, while in the latter, they mainly play an auxiliary role, such as supporting and suppressing the formation of dendrites. Depending on different situations, the requirements for MXenes are also different. As an active material for metal-ion batteries, it is expected that MXenes have enough active sites and low-diffusion barriers. As the host material of metal anode, MXenes should be able to effectively inhibit the extension of dendrites. As the host material of sulfur or a component of LSB separators, MXenes are usually required to block or inhibit the shuttle effect of polysulfides. Therefore, according to their different application purposes, MXenes with appropriate properties, suitable synthesis methods and reasonable morphology should be carefully selected or designed.

All in all, irrespective of the microstructure to the macro compositionor the foundation to the application, MXenes still have huge potential for improvement and development. In order to realize the commercial application of MXenes, one principle should be adhered to, which is that multifarious measures should be utilized to take full advantage of MXenes and avoid their disadvantages as much as possible. Incontrovertibly, the potential for MXenes to be used in next-generation rechargeable batteries is enormous, but considerable effort still needs to be made to achieve their commercial value.

In order to better reflect the application of MXenes in various post-lithium-ion batteries, a summary of the various related works is shown in Table 1.

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Conflict of interest

The authors declare that they have no conflict of interest.

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