



MXenes for sustainable energy: A comprehensive review on conservation and storage applications

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ABSTRACT

This review explores the potential of MXenes, a novel class of two-dimensional (2D) materials, in advancing energy storage and conservation technologies. MXenes exhibit exceptional physicochemical properties, including a high specific surface area ($\sim 390 \text{ m}^2 \text{ g}^{-1}$ for MXene@PPy-800), outstanding electrical conductivity, and robust chemical stability, making them ideal for energy-related applications. In supercapacitors, MXene-based electrodes have demonstrated capacitances exceeding 700 F g^{-1} at 1 mV s^{-1} , with retention of over 90 % of their initial performance after 10,000 charge/discharge cycles. For lithium-ion batteries, MXenes achieve theoretical capacities ranging from 390 to 600 mAh g^{-1} , depending on the type of MXene material, with experimental reversible capacities often exceeding 400 mAh g^{-1} at 1C rates and high cycling stability.

This review synthesizes recent research efforts on the synthesis, structural characterization, and integration of MXenes into energy storage systems. Findings highlight their versatility as electrode materials for supercapacitors, lithium-ion batteries, and fuel cells, as well as their catalytic potential in solar energy conversion. Despite these advancements, challenges remain unresolved. Scalability of MXene synthesis through selective etching methods continues to be a significant technical and economic barrier. Moreover, while MXene-based devices show high initial performance, further work is needed to improve long-term stability in operational and harsh chemical environments.

By providing a comprehensive overview of MXene-based energy systems, this review identifies critical gaps in understanding their electrochemical mechanisms, particularly ion transport and surface interaction dynamics. Addressing these challenges will be key to optimizing MXene properties and enabling their widespread application in efficient and sustainable energy technologies.

1. Overview

The research question addressed in this review is: how the recent advancements in MXene's synthesis and characterization addressed the challenges hindering their scalability and practical implementation in energy storage and conservation technologies? This question is pertinent because the rapid growth of the human energy needs coincides with the emergence of MXenes in the past two decades, which presents an opportunity to resolve the challenge in yet-to-be unravelled ways.

The structure of this report is as follows: firstly, it begins by establishing the research context; next, it examines the energy-related synthesis methods and resulting properties of MXenes like an importance of

Young's Modulus, aggregation and oxidation of MXenes; the focus then shifts to MXene-based composites and hybrids, highlighting their potential in energy-related applications like supercapacitors and batteries; finally, the review concludes by discussing energy-related applications and catalytic considerations for MXenes, while also outlining challenges and future research directions in this exciting field.

Energy conservation and storage are critical challenges in developing sustainable energy systems [1,2]. With the growing global demand for energy [3,4] and the finite nature of traditional fossil fuels, it is essential to find alternative energy sources that are both efficient and renewable [5,6]. Moreover, the need to reduce greenhouse gas emissions [7,8] and mitigate the negative impacts of climate change has made energy

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conservation and storage an even more pressing issue [9]. Developing sustainable energy systems capable of meeting society's energy needs while minimizing the environmental impact is a major challenge of our time [10].

In recent years, there has been growing interest in using two-dimensional (2D) materials for energy conservation and storage applications [11–13]. Two-dimensional transition metal carbides and nitrides (MXenes) have attracted significant attention due to their potential to enhance energy conservation efficiency [14,15]. MXenes are a class of layered structure materials that is only a few atoms thick, making them highly conductive and ideal for energy conservation and storage devices [16]. Properties of MXenes, particularly their large cross-sectional area and conductivity [17] make them well-suited for the use as electrodes in the energy storage devices, such as supercapacitors, batteries, and fuel cells [18]. Considering the energy commercial challenges, developing efficient energy conservation and storage systems is crucial. Using the 2D materials, such as MXenes, named to highlight a graphene-like morphology, can significantly enhance the efficiency of energy conservation and storage systems, significantly thereby contributing largely to developing sustainable energy systems. Therefore, the study of the properties and applications of MXenes in the energy conservation and storage is of great importance and a subject of ongoing research.

The typical unit cell structural formula for an MXene is $M_{n+1}X_nT_x$, where M represents an early transition metal (such as Ti, V, Zr, and Nb), X denotes carbon or nitrogen elements, and T signifies surface functional groups (such as –O, –OH, and –F) [19]. The value of 'n' ranges from 1 to 4 depending on the number of atomic layers in the unit cell, resulting in typical formulas of M_2XT_x , $M_3X_2T_x$, $M_4X_3T_x$ and $M_5X_4T_x$ respectively [20].

The first MXene, Ti_3C_2 , was introduced in the seminal work by Naguib et al. through wet-chemical etching in HF and exfoliation of the parent MAX phase Ti_3AlC_2 [21]. Their discovery in 2011 [22] marked a significant milestone in developing 2D materials and opened new avenues for energy conservation and storage research [23]. Since then, this two-dimensional material has sparked a surge in research, leading to the successful synthesis of nearly 40 MXenes to date, including $TiNbC$, Ti_2C , V_2C , Nb_4C_3 , Mo_2C , among others [24]. However, Titanium-based MXenes, particularly $Ti_3C_2T_x$, show greater promise for environmental remediation applications. Additional phases that have the structure $M_{n+1}X_nT_x$ have been predicted [25]

The rapid expansion of research on MXenes and energy-related applications unveiled over 43 200 publications between 2019 and 2024 according to Google Scholar, demonstrating that they can aid the development the sustainable energy systems. The study of the properties and applications of MXenes in the energy conservation and storage is of great importance. It can lead potentially to developing new and more efficient energy technologies. Despite the potential of MXenes for energy conservation and storage systems, many challenges still need to be addressed before they can be widely adopted. One of the major challenges is the stability of MXene-based devices over time [26], as the long-term stability of these devices has yet to be fully understood. This stability is critical for the practical use of MXenes in the energy conservation and storage systems [27]. Their unique physical and chemical properties are conditional by a structure consisting of two or more layers of transitional metals atoms packed into a honeycomb 2D lattice. Specific properties of MXenes and their composites such as high surface area, large conductivity, and excellent chemical stability, make them ideal for various energy-related applications [28–30] and can offer solutions for sustainable energy challenges.

The article provides an overview of several studies highlighting the intensive development of new materials and methods, with hundreds being created annually. Promising directions for future research include the optimization of synthesis techniques, the development of effective functionalization strategies, and the enhancement of structural stability to improve performance characteristics in conservation and storage applications.

2. Energy-related synthesis and properties of MXenes

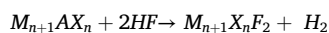
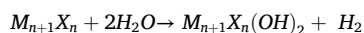
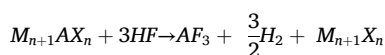
MXene production utilizes two primary strategies: top-down and bottom-up. Those strategies are common in Nanotechnology and allow for control over the surface chemistry and functionalization of the resulting material at certain extend. [31]. The first involves chemical etching, while the second concerns growing or depositing matter on seed atoms or molecules [32]. Although those two modes are well known in Nanoscience, there are also differences particular to MXene that will be discussed below.

2.1. Top-down approach of MXene production

There are various methods to obtain M-X layers, by removing the more reactive A layer. To split the A layers, various MAX phase etching methods have been investigated. The advantage of such synthesis method is that these methods allow to obtain a large number of MXene materials.

The current top-down approach in MXene is etching by pure HF or mixture of halogen (Br_2 , I_2 , ICl , IBr) acids such as HCl and fluoride salts [33]. It is a widely used technique in synthesizing and characterizing 2D materials, including MXenes, it involves the selective removal of layers from a stacked material using the various etching agent (See Fig. 1) [34].

MAX phase separation requires the use of an etchant to remove specific atomic layers of the material [35]. By removing the A layer, the metallic bonds between M and X are replaced by outer end bonds, which are comparatively weaker. Typically, these groups consist of –F (fluoride), –OH (hydroxyl), –H (hydrogen), or others [36] depending on the etchant. The resulting material has a multilayer structure in which the layers are held together by the van der Waals force [37]. Based on the study, when using this synthesis method, it is usually carried out at a heating temperature of about 55 °C and a holding time of 24–48 h or more. The MAX phase reaction using acidic lead occurred using HF, and the process followed the reaction described below [38]:



The final composition of MXene is highly dependent on factors such as HF concentration, duration, and temperature. Hydrofluoric acid is often used due to its efficiency and simplicity. However, its corrosive activity has a negative impact on the final product, thus there is a need to find the use of alternative etching methods. Studies show that a combination of hydrofluoric and hydrochloric acid to obtain *in situ* HF etching provides lower stability of the fluoride, which can also synthesize MXene with a weak structure. In turn, HF etching gives lower layer delamination, the *in situ* method requires additional delamination steps due to the –Cl end groups formed during the process [39].

In 2011, 50 % HF was used to selectively attack the (Al) layers of MAX phase Ti_3AlC_2 . After removing the (Al) layer, $Ti_3C_2T_x$ with a layered structure was obtained. The etching degree depends on the etchant concentration, etching time and temperature, since these parameters directly affect the physical and chemical properties of the obtained $Ti_3C_2T_x$. Wang et al. [40] investigated the effect of etching time on the HF etching of Ti_3AlC_2 . Using 1 g Ti_3AlC_2 with 20 mL of 40 % HF solution at 40 °C for 6–48 h, they observed distinct morphological changes. When the etching time was increased to 48 h, the compact layers transformed into an open accordion-like morphology. Long-term etching resulted in wafer failure and formation of corrosion holes in Ti_3AlC_2 sheets, resulting in a more pronounced step-resistant stage and improved exfoliation. This technique is used in MXene synthesis where by the bonds between the transition metal and higher reactivity element are broken. This action results in a layer consisting of the transition

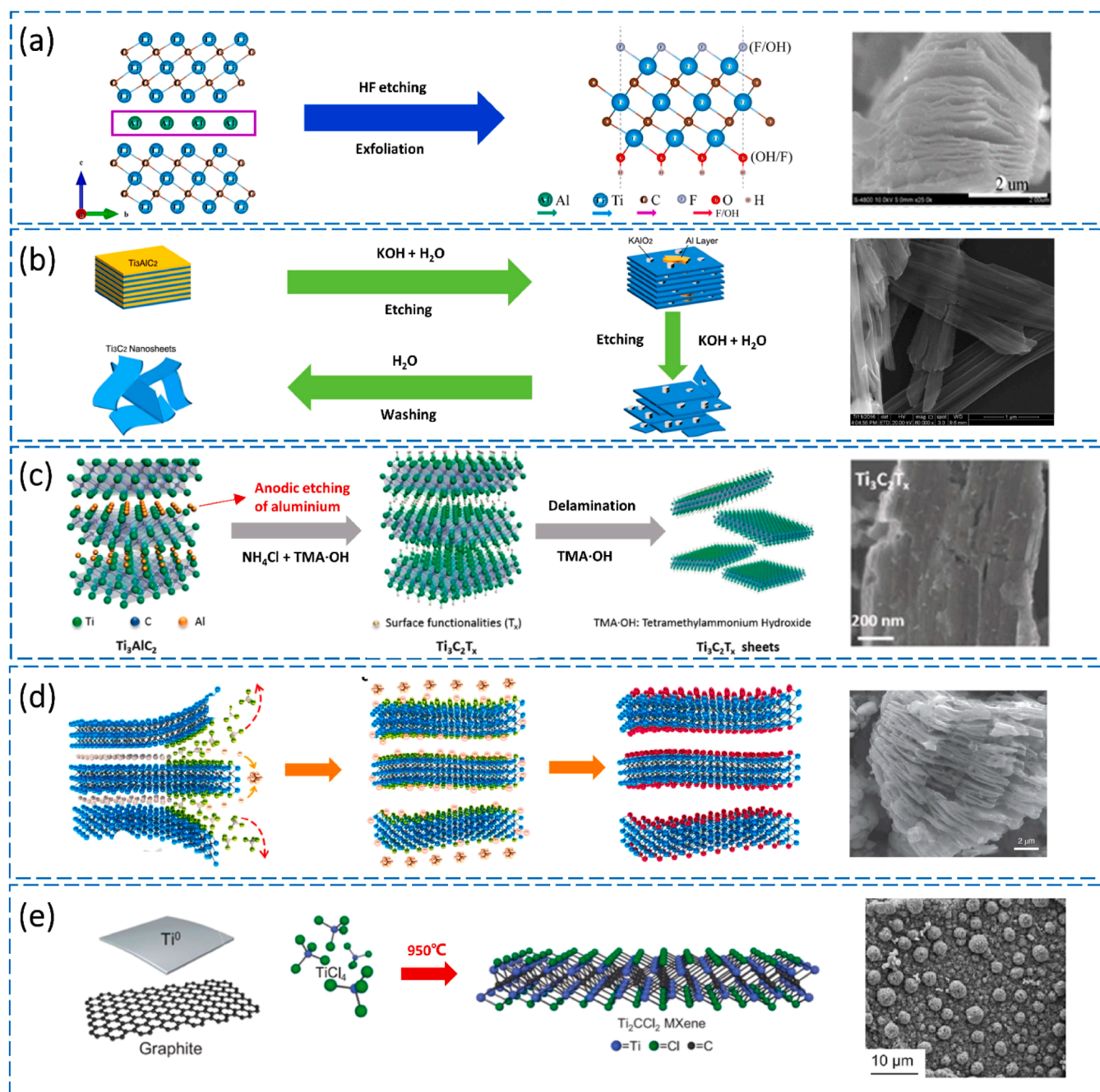


Fig. 1. (a) Synthesis and SEM of $\text{Ti}_3\text{C}_2\text{T}_x$. (b) Schematic illustration of the etching process and SEM for Ti_3AlC_2 . (c) Schematic of the etching process and SEM for Ti_3AlC_2 . (d) The reaction between Ti_3SiC_2 and CuCl_2 results in the formation of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and SEM. (e) Schematic diagram of the direct synthesis and SEM of Ti_2CCl_2 MXene [34].

metal and carbon [41]. The etching mechanism is based on the reactivity of the etching agent with the transition metal carbide (TMC) layer in the MAX phase. The transition metal carbide layer is more reactive than the other layers with hydrofluoric acid, allowing for selective removal [42]. HF can be used to modify the surface properties of MXenes by controlling the etching conditions and the time of exposure to HF [43]. For example, the exposed area and electrical conductivity of MXenes can be adjusted by controlling the etching conditions [44]. Notably, HF etching is an effective and scalable method for producing high-quality MXene materials [45] although hydrofluoric acid is highly reactive and hazardous.

Despite the success of the top-down production of MXenes, hydrofluoric acid is a highly corrosive and toxic material, and its handling

requires appropriate safety measures, including the use of protective equipment and the proper disposal of waste [46]. In addition, using HF carelessly in etching can also lead to the formation of defects and impurities in the MXene material, which can affect its performance in the energy conservation applications [47].

2.1.1. Molten salt etching

The synthesis of MXenes using molten salt etching has shown great promise due to its high yield, scalability, and lack of dangerous HF. Using this technique, MAX phases are heated at high temperatures, usually between 500 and 800 °C, in molten salts (such as ZnCl_2 , KCl, or NaCl). The A-element can be selectively removed from the MAX structure thanks to the molten salt's function as a reaction medium [48].

During this process, the molten salt and the A-layer combine to generate soluble intermediates, including AlCl_3 (for Al-based MAX phases), which can be eliminated during the post-synthesis washing procedures. Compared to HF-based processes, the process produces immaculate MXene flakes with few flaws and less environmental concerns. For example, it has been demonstrated that ZnCl_2 increases the etching effectiveness while also functionalizing the MXene surface with cholate groups, which can then be further altered for particular applications [49].

In the work by Rostami et al., they investigated the synthesis of Ti_3AlC_2 MAX phase in an air atmosphere by a molten salt-shielded method [50]. As shown in Fig. 2, $\text{TiO}_2\text{-Ti}_3\text{C}_2\text{Cl}_2$ MXenes were then produced by an *in situ* etching procedure employing the CuCl_2 Lewis acid salts technique at 750°C .

Recent developments have shown that molten salt etching enhances the electrochemical performance of MXenes in devices such as supercapacitors and batteries by providing fine control over the termination groups and layer thickness [51,52]. By enabling to synthesis of unconventional compositions, such as those with high-entropy components, this technique further expands the material library of MXenes.

2.1.2. Fluoride salt etching

Fluoride salt etching is a commonly utilized technique due to its versatility and simplicity. Typically, this method uses hydrochloric acid (HCl) and fluoride salts (such as LiF, NaF, or FeF_3) to selectively etch the A-element from MAX phases [53].

Fluoride ions react with the A-element to generate soluble fluoride complexes in the case of $\text{LiF} + \text{HCl}$ etching, and the acid dissolves these complexes to reveal the M layers [54]. Using lithium fluoride (LiF) salt and hydrochloric acid (HCl), Sarkar et al. studied the minimally intensive layer delamination (MILD) method for MXene synthesis [55]. It appears to be a better option due to its scalability and reproducibility, as well as its improved performance in various applications. As shown in Fig. 3, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene was created by selectively etching Al atoms from the Ti_3AlC_2 MAX phase using ($\text{LiF} + \text{HCl}$) in accordance with the MILD procedure.

Additionally, the method creates surface termination groups (-OH, -F, and -O), which improve MXenes' chemical activity and hydrophilicity. Alternative fluoride salts, such as CoF_2 and NaBF_4 , are utilized to customize the etching process by providing distinct surface terminations and better layer separation [56].

Numerous MXenes can be synthesized using this extremely flexible technique. For instance, MXenes with unique termination groups have been created using $\text{FeF}_3 + \text{HCl}$, which enhances their capacity for energy storage in devices like lithium-ion batteries [57]. However, the procedure usually uses dangerous chemicals, and it is still difficult to remove any remaining fluoride ions from the MXene surface for additional functionalization.

2.1.3. Alkali etching

As an alternative to acidic techniques, alkali etching uses strong bases such as NaOH or KOH to etch the A-layer. Because it does not require the use of dangerous HF or fluoride salts, this approach is very

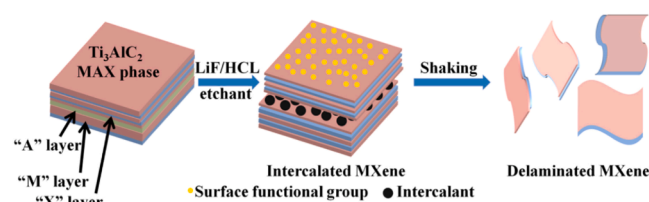


Fig. 3. The synthesis of MXene by the LiF/HCL etchant process. Reproduced with permission from Ref. [55].

beneficial for lowering the environmental effect of MXene synthesis [58].

The M-X layers are left behind after the A-element and base react to create soluble hydroxide complexes during alkali etching. For example, the removal of Al from Ti_3AlC_2 MAX phases can be facilitated by the use of magnesium hydride (MgH_2) as a reductant [59]. The resultant MXenes frequently have distinctive surface terminations (-OH and -O) that improve their electrochemical and catalytic capabilities [60].

Liu et al. proposed the electromagnetic absorption mechanisms and put out an efficient technique for delaminating single-layer MXene [61]. Fig. 4 shows the schematic depiction of $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets with varying surface terminals by different etching processes. Additionally, a multi-layer accordion structure of $\text{OH-Ti}_3\text{C}_2\text{T}_x$ was produced by selectively etching the Al layer in the MAX phase using an organic alkali etchant (TMAOH). Multilayer $\text{OH-Ti}_3\text{C}_2\text{T}_x$ nanosheets were produced following further dialysis. The TMAOH etching procedure and deionized water intercalation are responsible for the existence of -OH on the surface of $\text{OH-Ti}_3\text{C}_2\text{T}_x$.

Despite the advantages, alkali etching may need longer reaction times and produce lower yields than fluoride-based techniques. To increase effectiveness and scalability, developments in alkali etching condition optimization, such as the use of catalysts or mixed solvents, are being researched [62].

2.1.4. Electrochemical etching

A novel technique for synthesizing MXene, electrochemical etching uses an electrical potential to provide fine control over the etching process. With this technique, the A-layer is removed selectively by submerging the MAX phase in an electrolyte solution, usually one that contains fluoride or chloride ions, and then applying a voltage [63].

The electrochemical reaction causes the A-element to oxidize and dissolve, leaving behind layers of MXene. For instance, electrochemical etching in NaCl or NaF electrolytes has been used to create $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes [64]. By modifying the electrolyte composition and applied voltage, this technique allows for customizable surface chemistry.

In their study, Yin et al. suggested a gentle and environmentally friendly electrochemical exfoliation technique to create $\text{Ti}_3\text{C}_2\text{F}_x$ while simultaneously regulating the surface level of fluorination [65]. As seen in Fig. 5, MXene was created using a sealed three-electrode electrochemical etching setup.

MXenes with specific surface functionalization and few flaws can be synthesized by electrochemical etching. It is also scalable and eco-

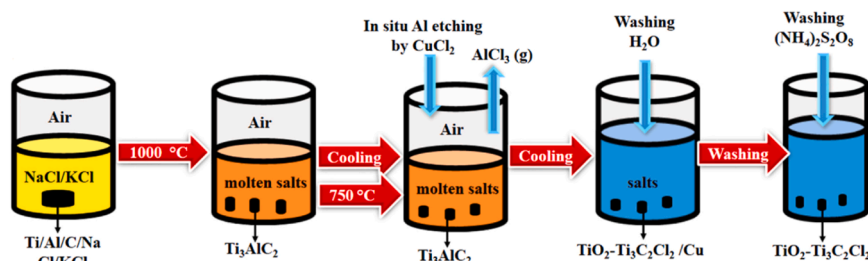


Fig. 2. The single-step molten salt preparation of $\text{TiO}_2\text{-Ti}_3\text{C}_2\text{Cl}_2$ MXene in an air atmosphere. Reproduced with permission from Ref. [50].

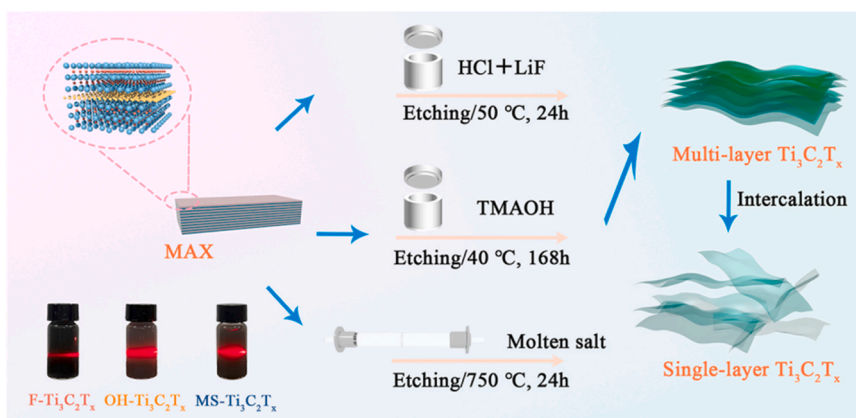


Fig. 4. Schematic representation of the MXene nanosheet synthesis steps with different surface terminals. Reproduced with permission from Ref. [61].

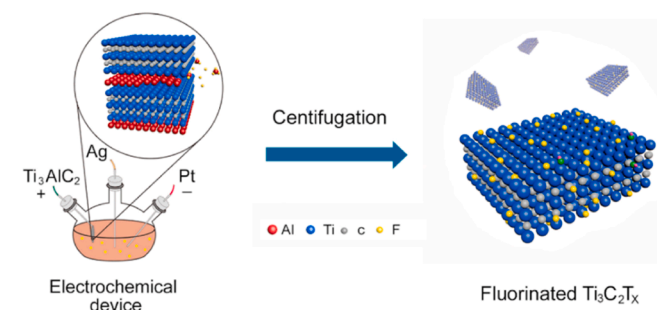


Fig. 5. Scheme of exfoliation of Ti_3AlC_2 and synthesis setup. Reproduced with permission from Ref. [65].

friendly, which makes it a viable substitute for chemical etching techniques. To prevent over-etching or insufficient A-layer removal, the procedure necessitates exact control over reaction parameters.

2.1.5. Summary

Overall, the chosen synthesis approach depends on the intended MXene characteristics and application, as each etching procedure has unique benefits and drawbacks. While fluoride salt etching is still flexible and efficient for creating different MXene compositions, molten salt etching offers a scalable and eco-friendly method. Electrochemical etching provides accuracy and sustainability but necessitates careful management, whereas alkali etching is a safer option but needs more tuning to increase yields. It is anticipated that further developments in these synthesis techniques will increase the uses of MXenes in energy storage, and other fields.

Other top-down synthesis methods have been developed to fabricate MXenes [66]. Those methods include ball milling and exfoliation [67]. First, ball milling [68] is a convenient method for the large-scale production of MXenes. In this method, the MAX phase is ground using a ball mill in the liquid medium (ethanol or water); process breaks down the MAX phase into smaller particles and generates defects, which lead to the formation of MXene layers [69]. Ball milling has advantages of being a simple and scalable method for producing MXenes, but also result in impurities and defects, which affect a quality of the resulting MXene material [70].

An alternative method to a ball-milling is exfoliation. Exfoliation involves the mechanical separation of MXene layers from the MAX phase exploiting various techniques, including sonication [71], mechanical exfoliation [72] and liquid exfoliation [73].

A variant of exfoliation is fragmentation which is applied in quantum dot matrix synthesis via cutting the 2D MXene nanosheets into slices of 10 nm or less [67]. Furthermore, exfoliation is an accessible and

effective method for producing high-quality MXene materials, but its challenging to scale up [74]. On the other hand, bottom-up approaches to MXene synthesis described below provide relatively safer and controllable ways to achieve some above-mentioned objectives.

2.2. Bottom-up approaches methods of MXene synthesis

Following the discovery of 2D MXene, researchers developed numerous techniques for synthesizing ultrathin materials. Among these, chemical vapor deposition (CVD) is the most widely used method for producing ultrathin materials with thicknesses as small as 58 nanometers (nm). The CVD process requires a substrate surface where chemical reaction precursors can interact to form thin films. These precursors must possess specific properties: they should be suitable for evaporation, volatile, of high chemical purity, and non-hazardous.

The shortcoming of top-down approaches has been is partly resolved using bottom-up approach known as template-assisted techniques. This technique includes chemical vapor deposition (CVD) [75] (see Fig. 6) [76] and plasma-enhanced pulsed-laser deposition, which are bottom-up approaches. They allow the precise control of the morphology of the MXene allowing producing high-quality MXene materials with tailored properties. CVD involves the deposition of precursor gases onto a substrate, where they undergo chemical reactions to form the desired MXene material [77]. CVD allows for the direct synthesis of MXenes from precursor gases, offering precise control over the composition, morphology, and properties of the resulting material. For example, superconductive ultrathin $\alpha\text{-Mo}_2\text{C}$ has been synthesised with higher structural quality and a larger size (over 100 μm) by a CVD process (at a temperature above 1085 $^\circ\text{C}$), as compared to defective MXene with a maximum size of $\sim 10 \mu\text{m}$ fabricated by chemical etching [74].

Wang and colleagues further synthesized Mo_2C using CVD, Mo_2C target deposition, and radio frequency magnetron deposition on a quartz wafer substrate. The sample was annealed at 600 $^\circ\text{C}$. The resulting MXene exhibited a thickness ranging from 4.3 to 4.7 nm. X-ray photoelectron spectroscopy (XPS) analysis revealed that Mo_2C contains Mo-O and C-O bonds, which may vary depending on the oxidation products of the target material [78].

In other studies, the synthesis process involves the reaction between methane or nitrogen gas and TiCl_4 on a Ti metal substrate, which results in the formation of Ti_2CCl_2 or Ti_2NCl_2 with terminal chlorine groups. Consequently, MXene layers are vertically generated from the metal surface and peeled off. The proposed CVD preparation method provides an opportunity for scaling up the production of MXene for commercial purposes [79]. For example, Ti_2NCl_2 prepared by this method showed chlorine-terminated MXene [80]. A downside of bottom-up synthesis is that it is a slow process and may produce low yields [80], also this alternative method is expensive and results in low productivity,

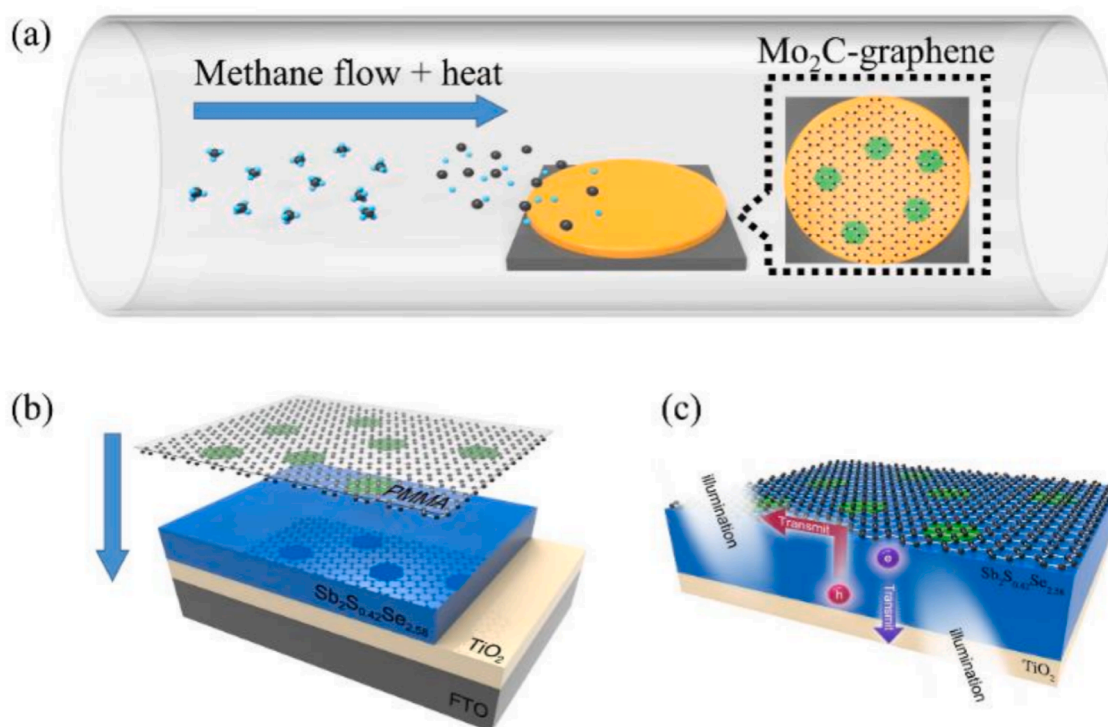


Fig. 6. The schematic diagrams of Mo₂C crystal growth and the novel Mo₂C—Gr/Sb₂S_{0.42}Se_{2.58}/TiO₂/FTO vertical heterostructure photodetector. (a) Schematic diagram of the chemical vapor deposition (CVD) method to grown Mo₂C—graphene. (b) The schematic diagram of the transfer of the Mo₂C—Gr layer. (c) The schematic diagram of the self-driven two-sided photodetector [76].

highlighting the need for further optimization to improve the efficiency and cost effectiveness of MXene preparation.

2.3. Properties of MXenes and challenges in practical applications

2.3.1. Young Modulus

An important consideration is the strengths of MXenes as measured using Young Modulus, an intrinsic property that is the ratio of tensile stress to strain. Certain MXenes emerge as promising contenders for electrodes with exceptional mechanical resilience against fatigue so it is important to understand their properties under mechanical duress [81].

Through a straightforward blading technique, MXene flakes can be spontaneously arranged into dense, self-supporting macroscopic layers [82]. These layers demonstrate impressive mechanical strength (with a tensile strength of 568 ± 24 MPa and a Young's modulus of 20.6 GPa for blade-coated Ti₃C₂T_x films) and fulfil the criteria for flexible anodes, courtesy of their flexibility and high electrical conductivity (measuring at $12,300 \pm 170$ S cm⁻¹) [83].

Previously [84], the Young's modulus of single-layer (SL) Ti₃C₂T_x was determined to be 0.33 ± 0.03 TPa, marking the highest value observed among all other solution-processed 2D materials, surpassing GO (~ 0.21 TPa) and MoS₂ (~ 0.27 TPa). However, this value stands at only one-third of the Young's modulus of pristine graphene (~ 1 TPa) [85]. These materials with high Young's moduli have proved more effective than metal-based anodes in scenarios demanding extensive charge-discharge cycles and electrode pliability. They are useful due to their outstanding mechanical and frictional characteristics [86]. It would be interesting to investigate modified MXene materials that exhibit values of Young Modulus similar to pristine graphene for electrical applications. Cracking this problem would open up the door for viable alternatives to dominance of graphene in electrical storage.

2.3.2. Aggregation of MXenes

Despite the potential of MXenes, several problems hinder their

practical use. The major issues include challenges related to aggregation and oxidation.

The main challenge for the application of MXenes is their aggregation in solution. This is due to the strong van der Waals interactions between the MXene layers, which make them restack and hence decrease the effective surface area available for electrochemical reactions. Such aggregation can severely limit the performance of MXenes in energy storage devices and composite materials [87,88].

Surface functionalization of MXenes with functional groups improves their dispersion stability. In this regard, functionalization with polymers or organic molecules can create steric hindrance, which could prevent aggregation [87]. Surfactants used during synthesis will be able to maintain a colloidal suspension of MXenes in a stable state. These agents may interact with the MXene surface, preventing them from coming close and aggregating [88].

Optimization of synthesis parameters such as pH, temperature, and concentration can reduce aggregation. Such tailoring of the conditions may result in smaller and more uniformly dispersed MXene flakes, improving their applicability in various fields [89].

2.3.3. Oxidation of MXenes

The oxidation of MXenes is another critical issue affecting their stability and performance. When exposed to moisture and oxygen, MXenes tend to form oxides on the surface, compromising their electrical conductivity and altering their chemical properties. Such degradation affects not only the effectiveness of the material but also its shelf life [90].

Application of protective coatings might prevent MXenes from environmental exposure to factors that lead to oxidation. Materials such as polymers or other 2D materials can serve as barriers against moisture and oxygen, preserving the integrity of the MXene layers [90].

In addition, the synthesis and processing, when carried out under inert atmospheres-like nitrogen or argon-significantly reduce the possibility of oxidation. This method, in particular, is very valuable at initial

stages of synthesis, in which the material usually presents a greater susceptibility to degradation [4].

The conductivity can be regained by applying several post-synthesis treatments after oxidation, including annealing under inert environments or chemical reduction methods. Such treatment might promote the removal of oxide layers grown due to air exposure [91].

2.3.4. Long-term stability of MXenes

MXenes, a novel class of two-dimensional materials, exhibit significant promise for energy storage and conservation applications due to their exceptional properties, including high electrical conductivity, large surface area, and chemical versatility. However, the widespread adoption of MXenes in practical energy devices is impeded by several challenges associated with their long-term stability.

One major issue is their chemical instability. MXenes, particularly $\text{Ti}_3\text{C}_2\text{T}_x$, are prone to oxidation when exposed to water, oxygen, or other reactive environmental conditions, leading to a degradation in conductivity and mechanical integrity. This oxidation significantly impairs the electrochemical performance of MXenes over time, especially in aqueous environments. Furthermore, MXenes are susceptible to restacking and aggregation during operation. The layers of MXenes tend to restack due to van der Waals interactions, which reduces the available surface area for charge storage and obstructs ion transport pathways. This phenomenon diminishes the overall efficiency and durability of MXene-based energy devices such as supercapacitors and batteries.

In addition to these issues, repeated cycling of MXene-based electrodes in energy storage devices can result in electrochemical degradation. This includes structural and compositional changes such as delamination, loss of functional groups, and the formation of defects, all of which compromise device performance. Thermal and mechanical fatigue also contribute to stability challenges, as MXene films, despite their flexibility, experience mechanical stress and thermal expansion/contraction during charge-discharge cycles. These stresses can cause cracking, delamination, and loss of contact between layers, further reducing the stability of MXene-based devices.

To address these challenges, various solutions have been proposed. One approach is surface functionalization and stabilization, which involves incorporating protective coatings, such as polymers or transition metal oxides, to shield MXenes from oxidation. The use of hydronium ions or other confinement strategies has also been shown to stabilize aqueous MXene suspensions and reduce oxidation rates. Additionally, functionalizing MXenes with groups such as fluorine or hydroxyl can enhance their chemical stability while maintaining conductivity.

Structural engineering, particularly through the introduction of interlayer spacers like carbon nanotubes or graphene, can prevent restacking and preserve efficient ion transport pathways. Optimizing flake size and morphology can further improve structural stability and mitigate aggregation. Electrolyte optimization is another avenue for enhancing long-term stability. By developing non-aqueous or ionic liquid electrolytes, it is possible to reduce the oxidative environment surrounding MXenes and prolong device lifespan. Furthermore, designing electrolytes with stable redox behavior can minimize side reactions and improve long-term cycling stability.

Mechanical reinforcement, achieved by combining MXenes with flexible substrates or composite materials, can also enhance their mechanical resilience against the stresses induced by charge-discharge cycles. Advanced fabrication techniques, such as laser crystallization or annealing, can improve the mechanical and thermal stability of MXene films. Additionally, bottom-up synthesis methods, such as chemical vapor deposition (CVD), offer a means to produce MXenes with fewer defects and greater intrinsic stability. Reducing the use of hazardous etching agents, such as hydrofluoric acid, in top-down synthesis can also minimize structural vulnerabilities.

Lastly, long-term performance monitoring through systematic studies on self-discharge behavior, aging effects, and degradation pathways under operational conditions is crucial for developing robust

MXene-based devices. *In-situ* monitoring techniques can provide valuable insights into the dynamic changes within MXene structures, thereby guiding future design improvements. By employing strategies such as surface modification, structural engineering, advanced synthesis techniques, and performance monitoring, researchers can enhance the stability and functionality of MXenes, unlocking their full potential for sustainable energy applications. Future work should focus on integrating these strategies and scaling them for industrial use to realize the promise of MXene-based energy devices.

3. Energy-related applications of MXenes

In the last few centuries, energy consumption along with the quality of life has been growing rapidly, which leads to faster depletion of traditional energy sources. Therefore, a number of developed countries are implementing generating capacities based on renewable energy sources. On the other hand, renewable energy sources are intermittent and often their generation schedule does not match the grid consumption schedule, which leads to energy losses. Therefore, it is necessary to implement energy storage systems to achieve energy conservation. For such purposes, energy storage devices are being developed based on various active electrode materials.

Transition metal carbides or nitrides make up MXenes, which have become promising materials for energy conversion and storage because of their high electrical conductivity, huge surface area, and rapid ion transfer. Because of these characteristics, MXenes can be used in a variety of applications, including as supercapacitors, batteries and solar energy storage systems. Table 1 provides performance data for MXene-based energy storage systems.

3.1. Supercapacitors

The supercapacitors are one of the most promising applications of MXenes in the energy storage. Supercapacitors (SC) have several advantages over traditional batteries, such as their ability to deliver high power density quickly and they can be charged and discharged many times without significant degradation [102]. These large-power energy storage devices can charge rapidly and discharge large amounts of energy, making them ideal for the use as regenerative braking systems in the electric vehicles and backup power sources for the renewable energy systems. The application of MXenes in capacitors naturally led to an interest in their application in batteries.

Better understanding of the fundamental energy conservation mechanisms in the MXene-based systems is necessary to develop more efficient and effective energy conservation technologies [103]. Several studies have addressed these challenges [104–107] with the researchers exploring new synthesis methods and the fundamental mechanisms of energy conservation in the MXene-based systems. There have been the

Table 1
A performance data for MXene-based energy storage systems.

Name	Capacity	Current density	Energy storage type	Refs.
p-Ti ₃ C ₂ T _x /CNT	1250 mAh/g	0.1 C	Li-ion	[92]
RuO ₂ @MXene	864.2 F cm ⁻³	1 mV/s	supercapacitor	[93]
V ₂ C ₂ T _x	380	1 C	Li-ion	[94]
MXene 'paper'	410 mA h g ⁻¹	1C	Li-ion	[95]
MoS ₂ /	554 mAh g ⁻¹	100 mA/g	Li-ion	[96]
Mo ₂ TiC ₂ T _x -500				
S-Ti ₃ C ₂ MXenes	135 mAh g ⁻¹	2 A g ⁻¹	SIB	[97]
u-CoTDA	790 mAh g ⁻¹	1 A g ⁻¹	Li-ion	[98]
Q ₃ M ₇	1560 F cm ⁻³	20 A cm ⁻³	supercapacitor	[99]
MoS ₂ /NiMnIn/SS	487.86 F.g ⁻¹	0.7 A.g ⁻¹	supercapacitor	[100]
TFE				
MoON/SSM	30.7 mF cm ⁻²	0.125 mA cm ⁻²	supercapacitor	[101]

studies aimed at understanding the electrochemical properties of MXenes and the mechanisms of energy conservation in the MXene-based supercapacitors [108].

MXenes have gained significant attention for their exceptional electrochemical properties in applications such as supercapacitors and metal-ion batteries. Feng group reported the successful synthesis of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene through the selective etching of the aluminum layer from the Ti_3AlC_2 MAX phase using hexafluorozirconic acid and they achieved outstanding energy and power densities, along with a capacitance retention of 86 % after 10,000 cycles by employing $\text{Ti}_3\text{C}_2\text{T}_x$ MXene as the negative electrode and activated carbon as the positive electrode in an asymmetric ammonium-ion capacitor (7.21 mWhg^{-1} at a power density of 1260 mWg^{-1}) [109].

Luo et al. [110] reported the increased SC of N- Ti_3C_2 can be largely explained by the presence of more accessible pathways for H^+ ions among significant number of active sites for electrochemical reactions and the reduction of $-\text{F}$ terminal groups. They exhibited the N- Ti_3C_2 film electrode achieved an SC of 1609.5 F g^{-1} at an SR of 2 mV s^{-1} in a $3 \text{M H}_2\text{SO}_4$ electrolyte.

In the supercapacitors, MXenes were proven to have a high specific capacitance, making them suitable as electrodes for the energy storage (see Fig. 7) [111].

The great conductivity of MXenes enables fast charge and discharge rates, which are crucial for the high-power applications [112]. MXenes were also investigated for the use in the fuel cells [113], where their great conductivity and stability make them suitable for the use as catalysts or electrodes. Because a fuel cell performance relies on the efficient movement of charge between the anode and cathode, MXenes' high conductivity facilitates this process, leading to improved performance [114].

Supercapacitor's performance is based on faradaic pseudocapacitance of two-dimensional or quasi two-dimensional at which redox process can occur [115]. In practice, MXene-based electrodes have demonstrated exceptional volumetric capacitances, reaching an impressive 900 F/cm^3 , which translates to specific capacitances of 245 F/g [116]. Remarkably, even under the demanding conditions of a relatively high current density of 10 A/g , the specific capacitance remained nearly constant after an extensive cycling process of 10,000

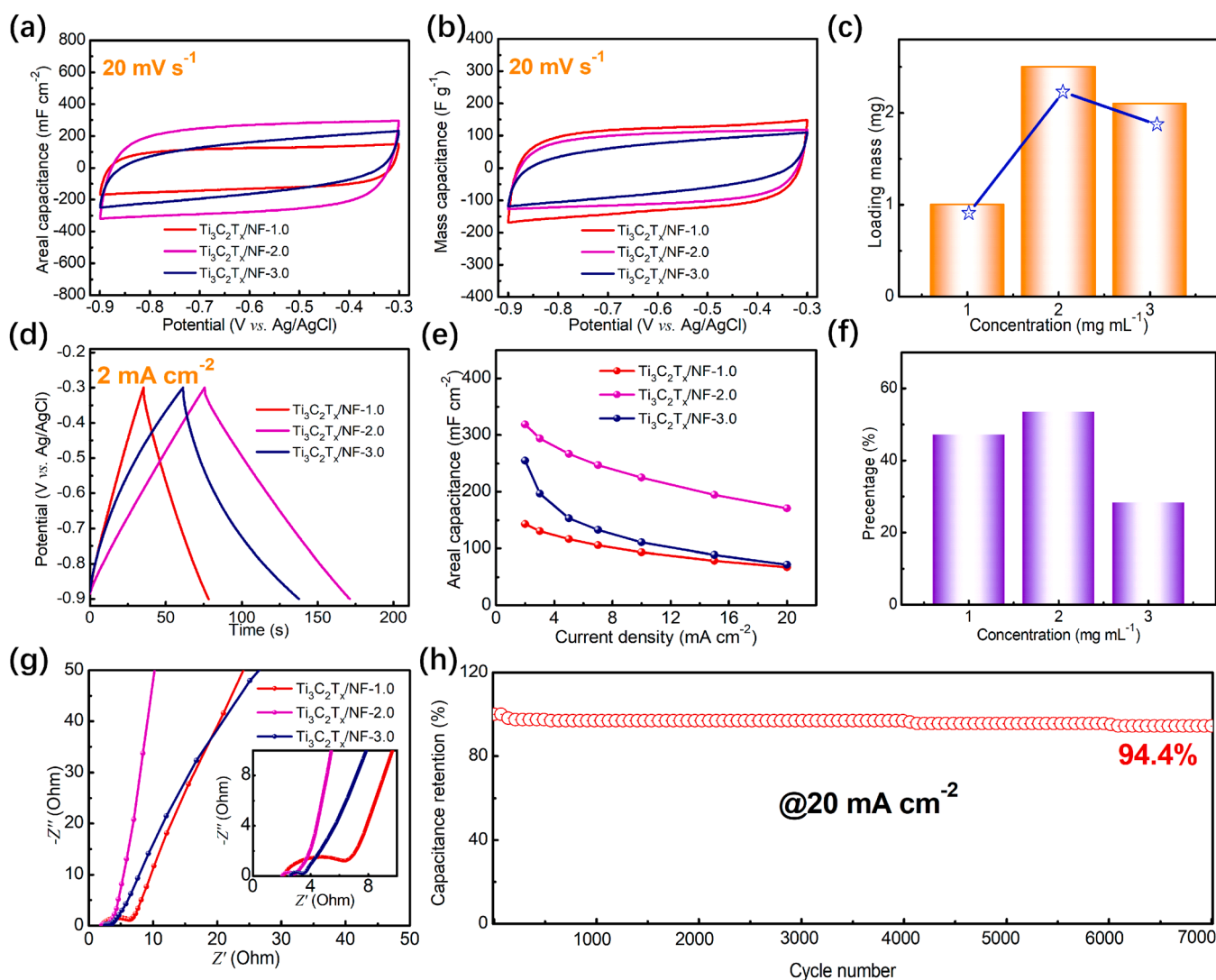


Fig. 7. (a) The cycle voltammogram (CV) curves of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-1.0$, $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-2.0$, and $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-3.0$ electrodes for areal specific capacitance at 20 mV s^{-1} . (b) The CV curves of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-1.0$, $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-2.0$, and $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-3.0$ electrodes for mass specific capacitance at 20 mV s^{-1} . (c) The loading mass of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-1.0$, $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-2.0$, and $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-3.0$ electrodes. (d) The galvanostatic charge-discharge (GCD) curves of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-1.0$, $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-2.0$, and $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-3.0$ electrodes at 2 mA cm^{-2} . (e,f) The performance rates of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-1.0$, $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-2.0$, and $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-3.0$ electrodes. (g) The electrochemical impedance spectroscopy (EIS) curves of the $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-1.0$, $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-2.0$, and $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-3.0$ electrodes. (h) The capacitance retention of $\text{Ti}_3\text{C}_2\text{T}_x/\text{NF}-2.0$ after 7000 cycles at 20 mA cm^{-2} [111].

cycles [117].

MXenes exhibit outstanding capacitance (300–500 F g⁻¹), surpassing most carbon materials, and demonstrate excellent cycle stability, outperforming conventional pseudocapacitive materials [118]. Moreover, MXenes offer ultrahigh volumetric capacitance, with values reaching 900–1500 F cm⁻³, exceeding other electrode materials [119]. Their metallic-like conductivity ensures outstanding high-rate performance, with conductivities much higher than other 2D materials. MXene suspensions can be easily prepared in various solvents, simplifying processing [120]. Despite challenges such as horizontal aggregation and restacking limiting practical capacitance, strategies like controlling flake size and introducing carbon spacers show promise in enhancing MXene performance [121].

MXene-coated carbon nanofibers (CNFs) were studied by Kyung et al. [122] as potential supercapacitor electrode materials. CNFs were dip-coated Ti₃C₂ MXene colloidal solutions, resulting in an energy and power density of 71.4 Wh/kg and 2.3 kW/kg, respectively, and a specific capacity of 514 F/g at 0.5 A/g. The pseudocapacitive nature of MXenes was responsible for the electrodes' exceptional cyclic stability over 5000 cycles. Multilayer Ti₃C₂T_x MXenes were investigated by Tsyganov et al. as electrodes for symmetric supercapacitors in aqueous LiCl electrolytes [123]. With a broadened potential window from 0.7 V to 1 V, the specific capacitance rose from 105 F/g (1 M) to 151 F/g (20 M) at 5 mV/s. After 10,000 cycles, the supercapacitors maintained 88 % of their capacitance, demonstrating good cycling stability. The efficiency of binder-free MXene inks for supercapacitors was shown by Thirumal et al. [124]. When applied directly on Ni foam, Ti₃C₂T_x nanosheets demonstrated greater cycle stability than binder-based electrodes and provided a specific capacitance of 105.75 F/g at 1 A/g, making them a scalable alternative for energy storage devices.

In Wang et al. [125], a theoretical determination of Gibb's free energy of formation, ΔG , for Ti₃CN and V₂C led to the conclusion that the former was with higher values of ΔG was less chemically stable than the later in all the face-centred cubic, hexagonal close packed (HCP) and atop configurations. The respective values of ΔG obtained per oxygen terminating molecule for these sites were 0.00, 0.372 and 1.396 for V₂C and 0.00, 0.880 and 2.395. However, further work needs to be done concerning the MXenes derived from other transition metals. Interestingly, for the Ti₃CN MXene, the ΔG values for face-centered cubic (FCC), HCP and atop were higher for the carbon side of the molecule than for the nitrogen site yielding 0.250, 1.137 and 2.805 on the one hand and 0.000, 0.873 and 2.234 on the other hand, respectively. However, all above was accomplished using computational techniques and yet to be tested in a physical laboratory setting. Zhang et al. [126] stabilized the aqueous MXene solutions of Ti₃C₂T_x via using a low-cost hydronium ion as confinement shield layers for adsorption, aggregating and contracting its nanosheets. This action raised the Gibb's free energy subverting spontaneous oxidation of Ti₃C₂T_x. The stabilized MXene held in the temperature range 25–60 °C and produced the same results including a specific capacitance of 233 Fg⁻¹ at 10 mVs⁻¹ as freshly made Ti₃C₂T_x after 50 days of storage. Overall, MXenes hold significant potential for advancing supercapacitor technology through their unique combination of properties.

Concerning supercapacitors, transparent and electrically conductive Ti₃C₂T_x films exhibiting a volume capacitance of 676 F/cm³ and fast electrochemical reactivity have been developed and tested. Zhang et al. [127] used such Ti₃C₂T_x films to create transparent solid-state supercapacitors. The team employed a spin-casting technique to expertly collect the MXene transparent films from colloidal suspensions of Ti₃C₂T_x nanosheets and then heat-treated them in a vacuum at 200 °C. Notably, the 4 nm and 88 nm thicknesses provided 93 % and 29 % transparency, combined with DC conductivity of 5736 and 9880 S/cm, respectively. Presumably, the transparency of supercapacitors supports diagnostic maintenance. Transparency allows for the direct visual inspection of the internal components without the need for disassembly. This can help in identifying issues such as electrode degradation,

electrolyte leakage, or other physical defects

Simultaneously, efforts were extended to assembling transparent solid-state asymmetric supercapacitors with an optical transparency of 72 %. This was achieved by integrating hybrid films, a mixture of Ti₃C₂T_x, and single-walled carbon nanotubes. These electrodes proudly displayed a capacitance area of 1.6 mF/cm², corresponding to an energy density of 0.05 μ Wh/cm², and impressively maintained long-term stability spanning over 20,000 cycles.

The first MXene supercapacitor suffered plate oxidation and degradation in the presence of water [128]. Treatment with tartaric acid prevented the MXene from oxidizing. MXene-based supercapacitors suffer from self-discharge, but altering the oxidation state and coordination features of the MXene can reduce this tendency [129]. Additional improvements are possible in plate area and the number of charging-discharging cycles, which can be realized using laser crystallizations [130]. Vanadium carbide MXene has shown 209 F/g at 2 mV/s with extended and stable cycling [131]. However, it is unclear whether the results of vanadium based MXene are the best possible. Annealing treatment might improve the structure and electrochemistry of 2D MXene [131,132]. Therefore, further work in developing supercapacitors is needed in anode research, stability, charge leakage prevention, plate area, longevity, MXene type and annealing.

3.2. Rechargeable-ion batteries

While the self-discharge of MXene based capacitors and supercapacitors has been investigated with promising functionality and performance [133], similar work on batteries is still unexplored territory. Batteries have been designed with a lithium cathode and MXene anode although self-discharge studies for such batteries does not appear to exist [134]. However, the self-discharge behavior of other lithium-based batteries has been investigated in terms of Gibb's free energy in the presence or absence of barriers between the anode and cathode. For example, High entropy MXene (HE-MXene) TiVnNbMoC₃ catalyses the lithium polysulfide redox reaction within the cell, achieving extended cycling with a low self-discharge rate of 0.026 % per cycle after 1200 cycles at 1 C. The transition metal (TM) and the exposed active sites in HE-MXene contribute to the process. Moreover, the HE-MXene cell delivers 40 mAh cm⁻² for 6000 cycling hours, which means the cell can be charged and discharged many times without significant degradation [135].

Khan et al. [136] reported highly effective fluorine free Ti₃C₂T_x MXenes with enhanced electrochemical properties which obtained by varying etching time and temperature. The synthesized Ti₃C₂T_x MXenes exhibit distinct charge-discharge performance and impressive battery-like characteristics when tested in a 1 M H₂SO₄ electrolyte. Especially, the 6D-160 °C sample shows relatively superior gravimetric capacity of 450 C g⁻¹ with a retention rate of 114 % after 8000 cycles, compared to the HF-etched sample.

Additionally, Guo et al. focused on the usage of MXenes to boost the performance of lithium-ion batteries by combining them with α -MoO₃, a pseudocapacitor material with a high theoretical capacity of 1117 mAh/g but low conductivity [137]. To enhance Li⁺ diffusion kinetics, a free-standing α -MoO₃/MXene composite electrode was created, utilizing MXene's remarkable electrical conductivity and mechanical adaptability. A complete cell with commercial LiFePO₄ as the cathode showed outstanding rate performance (48 mAh/g at 1 A/g) and a high Li⁺ storage capacity of 160 mAh/g. The promise of MXenes for sophisticated, binder-free electrodes in high-performance Li-ion batteries is demonstrated by this study.

Lithium-ion batteries are devices for energy storage consisting of two electrodes — a cathode and an anode — that convert energy from electrical to chemical during charging and vice versa during discharging. Currently, there is a significant amount of research focused on both cathode and anode materials. In commercial lithium-ion batteries, graphite is commonly used as the anode, with a theoretical capacity of

up to 378 mAh/g. However, in practical conditions, its capacity does not exceed 280–290 mAh/g, which is considerably lower than its theoretical value. The main issue with graphite is its limited capacity, which restricts the overall energy density and efficiency of lithium-ion batteries.

As a result, there has been active research focused on modifying existing anode materials or replacing them with more promising alternatives. One such material is MXene, a class of two-dimensional materials that possess unique physicochemical properties, such as high electrical conductivity, large surface area, and chemical versatility. MXene-based anodes offer the potential for significantly greater energy storage compared to traditional graphite anodes, making them promising for use in lithium-ion batteries.

One of the key advantages of MXene is its high conductivity and surface activity, which enhances ion transport properties and increases capacity. Additionally, MXene has high mechanical strength, contributing to improved stability and longevity of batteries. However, to fully unlock the potential of MXene as an anode material, several challenges need to be addressed, such as its chemical instability in aqueous and acidic environments, tendency to aggregate, and low stability during cyclic operation. To overcome these issues, methods for surface functionalization of MXene, as well as advancements in synthesis technologies and material structure optimization, are being actively developed.

Researchers have synthesized few-layer Nb₂CT_x nanosheets and accordion-like multilayer Nb₂CT_x, with the aim of producing f-Nb₂CT_x MXene via a single-step HF etching process. The f-Nb₂CT_x material exhibits a high specific capacity of 354 mAh·g⁻¹ at a current density of 0.05 A·g⁻¹ after 110 cycles. Furthermore, its specific capacity can be stabilized at 225 mAh·g⁻¹ even after 800 cycles at 1.0 A·g⁻¹, demonstrating that f-Nb₂CT_x with a 2D structure is a promising high-performance anode material for lithium-ion batteries, offering long cycle life and excellent cyclic stability [138].

Another type of material is CoSe₂. New CoSe₂/Ti₃C₂T_x composites with high specific capacity and excellent stability were successfully synthesized by *in situ* growth of CoSe₂ particles on Ti₃C₂T_x using a hydrothermal method. The results demonstrated that after 1000 charge-discharge cycles at a current density of 0.3 A·g⁻¹, the CoSe₂/Ti₃C₂T_x composite (with a molar ratio of 1:2) retains a high reversible capacity of 210.8 mAh·g⁻¹ [139].

Nb₂CT_x MXene was synthesized using an acid molten salt method at a temperature of 750 °C. The chemical properties of the resulting Nb₂CT_x MXene contribute to its excellent electrochemical performance, achieving a maximum specific capacity of 330 mAh·g⁻¹ and maintaining high performance at 80 mAh·g⁻¹ at 100 °C. These results demonstrate the significant potential of Nb₂CT_x MXene as a promising anode material for lithium-ion batteries [140].

Concerning batteries, authors [141] et al. demonstrated how the Ti₃C₂ MXene is superior to graphite in lithium-ion battery (LIB) anodes. They prepared few-layered Ti₃C₂ MXene through microwave-assisted *in-situ* etching. MXene aiming to enhance electrochemical efficiency via varying the ratio of activated carbon (AC) to Ti₃C₂ the initial specific capacity of 1194.2 mAh/g at a current density of 0.2 A/g and retaining over 841.8 mAh/g after 80 cycles with nearly 100 % Coulombic efficiency was achieved. Tang et al. employed computational chemistry technics to determine the outputs for various configurations of the Ti₃C₂ MXene. While they generated interesting predictions, it is possible that the predictions do not match what actual experiments could reveal. It is interesting to test the Tang et al. predictions experimentally [142].

Relatedly, Sun et al. [143], produced 2D Ti₃C₂ intercalated with dimethyl sulfoxide, the resulting MXene served as anode material for lithium-ion batteries. The intercalation step resulted in a specific capacity of 123.6 mAh/g at a rate of 1 C, accompanied by a Coulomb efficiency of 47 % surpassing that of 2D Ti₃C₂. It approached the Tang et al. [142] theoretical capacity of Ti₃C₂. However, Sun et al. did not investigate the effect of termination with pure fluorine (F) functional group on the electrochemical properties of the MXene. This gap offers a line for experimental research [143].

For energy storage applications, MXenes have shown themselves to be adaptable materials. High specific capacitance and cycling stability improve supercapacitors' performance [144,145] and enhanced charge capacity and cycling stability increase lithium-ion battery efficiency [146].

3.3. MXene-based composites and hybrids in various applications

The broad surface area of up to 183.8 m²/g [147], electrical conductivity and excellent chemical stability of modified MXenes makes them ideal for various energy-related applications, including supercapacitors, batteries, fuel cells and solar energy conservation.

One approach to improve the MXene performance characteristics is to modify the containing material which catalyses the operations. One approach to improve MXene performance is to modify the composite material to enhance its activity for desired functions. In this sense, MXenes-based composites and hybrids comprise MXenes and other materials, such as polymers, metals, and ceramics [147]. These materials have been extensively investigated in recent years due to their potential in the energy storage and conservation applications [148]. Combining the properties of different materials, the MXenes-based composites and hybrids can improve performance compared to the individual materials [149]. The MXene-based composites were successfully used as electrodes in the energy storage devices such as supercapacitors, batteries, and fuel cells [150]. For example, MXene-polymer composites were proved to have a great capacitance, long cycle life, and good rate capability [151]. Adding polymers to MXene can potentially reduce the cost, improve stability, and enhance mechanical flexibility of the electrodes, making them more suitable for practical applications. [152]. Similarly, the MXenes-based hybrids were used as photocatalysts in the solar energy conservation [153]. Additionally, the Ni-Co-Fe-P MXene-based hybrids are effective catalysts for the oxygen evolution reaction (OER) in water splitting, which is an important reaction in the generation of hydrogen fuel from water [154]. When different metals are combined to form hybrids, the resulting materials not only exhibit improved catalytic activity and stability but also benefit from enhanced functional properties. For example, these hybrids can achieve better electrical conductivity, increased mechanical strength, and greater thermal stability. Such enhancements make them highly suitable for a variety of applications, including supercapacitors, batteries, and electronic devices. By exploiting the unique qualities of each metal, these hybrids can be precisely engineered for specific uses, thus delivering superior performance across multiple fields. Besides their use in the energy storage and conservation systems, the MXenes-based composites and hybrids were exploited in the other applications, such as electromagnetic energy shielding and catalytic oxidation reactions where lowering activation energy is advantages [84].

Electrodes utilizing hybrid films composed of Ti₃C₂T_x and Ag demonstrated notable characteristics, including a substantial specific surface area of 107 m²/g, a remarkable areal capacitance of 332.2 mF/cm at a scan rate of 2 mV/s, significant capacitance preservation of 63.2 % when transitioning from 2 to 100 mV/s, and an impressive cycling stability of 87 % after undergoing 10,000 cycles [155]. This large surface area is obtained due to the inter-layer spacing between the stacked MXene layers, ranging from a few angstroms to a few nanometres [156]. In contrast, the electrical conductivity of Ti₃C₂T_x exhibits a significantly heightened metallic character when compared to the majority of MXenes documented in the existing scientific literature [157]. Authors [158] reports a synthesis of Ti₃C₂T_x nanoflakes with limited number of defects and an electrical conductivity of 6.5 × 10⁻³ S/cm. Nonetheless, when the same Ti₃C₂T_x sample possesses a significant number of defects, particularly resulting from the HF utilisation as the etching agent the electrical conductivity could fall below 1000 S/cm [159]. The lateral size of MXene enables the efficient charge storage and enhances energy conservation efficiency in MXene-based devices, such as

supercapacitors, batteries, and fuel cells [160]. Furthermore, the high specific surface area of MXenes also enables their use as catalysts in the solar energy conservation, as they can provide a big surface area (approximately $1139.00 \text{ m}^2/\text{g}$ for $\text{Ti}_3\text{C}_2\text{T}_x$ based Metal Organic Framework nanocomposites) for the efficient absorption of light and conversion of energy [161]. Notably, pristine MXenes lack energy band gaps so that at the time of writing, there no known instances of them initiating photocatalytic activity for energy production.

In addition to their use as electrodes, MXenes such as $\text{Ti}_3\text{C}_2\text{T}_x$, Ti_2CT_x , V_2CT_x , and Nb_2CT_x [162] have been shown to catalyse solar energy conversion processes [163]. The chemical stability and huge exposed surface of MXenes make them suitable for the use as catalysts in such photochemical reactions as water splitting [164] and CO_2 reduction [165], where they can enhance the efficiency of energy conservation processes [166]. Investigating catalytic MXenes that are based on other transition elements for energy applications is an ongoing field of study.

On top of that, MXene aerogels as potential solar energy carriers, were created by Wang et al. to encapsulate polyethylene glycol (PEG) in phase change materials (PCMs) [167]. High PEG loadings of up to 97 % were made possible by these aerogels with negligible effects on enthalpy and phase transition temperatures. The composites outperformed several current PCM systems with their remarkable thermal cycling stability, maintaining 97.7 % of their heat storage capacity after 500 cycles, and their 93.5 % solar energy usage efficiency. The doping of paraffin wax (PW82) with MXenes (TiC_2) and TiO_2 nanoparticles to improve the thermal characteristics of PCMs was studied by Khan et al [168]. In addition to a 6 % rise in the dissociation temperature, hybrid doping at 0.3 % increased thermal conductivity by 15.6 % and specific heat capacity by 41.3 %. The potential of hybrid nano-enhanced PCMs (NEPCMs) for effective heat storage applications is highlighted in this work. Moreover, in their fabrication of MXene-wrapped wood-derived porous carbon substrates for PCMs, Chen et al. achieved improved photo-thermal conversion efficiency (90.1 %) and thermal conductivity (0.69 W/m-K) [169]. Their composites demonstrated wide-ranging uses in solar thermal absorption and heat storage, and they also effectively managed heat for electronic equipment.

Despite the progress on MXenes reflected in research texts much work must be done before MXenes can be extensively used in the energy conservation and storage systems, that take advantage of higher capacity, optimum discharge rates and greater durability.

4. Challenges and future perspective

MXenes have gained attention as highly promising materials for sustainable energy systems due to their excellent electrical conductivity, large surface area, and customizable surface chemistry. However, despite their significant potential in energy storage and conservation, several barriers hinder their widespread implementation. One of the key issues is their synthesis, which frequently relies on hazardous substances like hydrofluoric acid, raising concerns about environmental safety and scalability. Additionally, existing methods struggle to produce high-quality MXenes at scale without compromising their structural integrity and desirable properties.

Another major challenge lies in their surface chemistry and stability. MXenes are prone to oxidation under ambient conditions, which can drastically diminish their performance. Achieving precise control over surface terminations to tailor their functionality for specific energy storage applications remains an ongoing area of research. Furthermore, integrating MXenes into energy devices such as supercapacitors, batteries, or fuel cells requires compatibility with other materials and the ability to maintain stability and structural integrity during repeated charge-discharge cycles.

The environmental and economic sustainability of MXenes also requires attention. While they hold great promise for advancing clean energy technologies, their production processes must minimize

environmental impacts. Additionally, their high synthesis costs make them less competitive compared to other materials, highlighting the need for cost-effective and environmentally friendly production methods.

Future progress depends on advancing synthesis techniques, particularly those that eliminate hydrofluoric acid and adopt environmentally sustainable approaches, to enable scalable MXene production. Strategies for precise functionalization at the atomic level, especially in surface chemistry, will be critical to optimizing performance for targeted applications. Hybrid and composite materials combining MXenes with graphene or polymers also show great promise for improving mechanical stability and enhancing energy storage capabilities. Beyond conventional energy storage, MXenes hold potential for innovative applications like hydrogen production and thermoelectric energy harvesting. Computational tools, including density functional theory and machine learning, are expected to play a pivotal role in predicting optimal configurations and accelerating material discovery. Standardized protocols for evaluating performance will further enhance consistency and reproducibility in research.

To unlock MXenes' full potential in sustainable energy systems, addressing challenges such as long-term stability, environmental impact, and lifecycle management is essential. Prioritizing recyclability and aligning production practices with circular economy principles will solidify their role in a greener future. By tackling these challenges through interdisciplinary collaboration, MXenes have the potential to revolutionize energy conservation and storage technologies, shaping a more sustainable energy landscape.

5. Conclusion

The unique physical and chemical properties of MXenes and the potential for tailoring their properties make them attractive for the use as electrodes in the energy storage and conservation systems a few challenges notwithstanding. Several synthesis methods have been developed for producing MXenes in energy conserving and storage. These techniques include hydrofluoric acid (HF) etching, ball milling, exfoliation, and template-assisted synthesis. Each method has advantages and disadvantages, and the choice of synthesis depends on the specific requirements and applications of the MXene material. Currently, HF etching has gained significant traction and shown considerable potential in MXene production for energy storage applications.

However, the existing MXenes for energy applications offer advantages individually and present many disadvantages. It is important to investigate alternative synthesis approaches, develop MXene with more encompassing advantages while introducing fewer disadvantages in energy storage devices. Ultimately, determining the optimal MXene synthesis method for energy conservation and storage is a multi-faceted quest requiring careful evaluation of the intended performance characteristics, scalability, and economic viability. Despite their potential, many challenges are still associated with using the MXenes-based composites and hybrids. For example, synthesizing the MXenes-based composites and hybrids is often challenging as it requires a precise control of the composition, structure, and interface between the different materials. Moreover, the choice of an appropriate synthesis method also depends on the MXene variant required for the energy source application, such as battery development, supercapacitor, pseudocapacitor, fuel cells and solar panels. For example, while $\text{Ti}_3\text{C}_2\text{T}_x$ is a common MXene, other variants such as $\text{Mo}_2\text{TiC}_2\text{T}_x$ show better energy storage potential.

Interestingly, while MXene hybrids show good promise as anodes, they may adversely affect chemical compatibility and electrical conductivity. Furthermore, the use of MXenes and their hybrids produce results that do not conform to present industry standards for charge storage devices, hence requiring additional study. While the electrochemical properties of MXenes have received attention, much

exploration is still possible concerning the chemistry of materials, etching, reliability, chemical degradation, longevity, capacity, scalability, and cost. Further work is possible in MXene synthesis, surface chemistry and computational simulations.

There is a need for more comprehensive studies to understand better the properties and mechanisms of energy conservation in the MXenes-based composites and hybrids. Further research is needed to optimize the use of MXenes in the energy storage and conservation systems and to advance developing the sustainable energy technologies. Researchers should focus on exploring novel synthesis methods, structural modifications, reducing degradation and improving cycling stability, without experiencing substantial deterioration in performance.

CRediT authorship contribution statement

Mirlan Jussambayev: Writing – original draft, Investigation. **Kalizhan Shakenov:** Supervision, Project administration. **Shyngys-khan Sultakhan:** Data curation. **Ulan Zhantikeev:** Visualization. **Kydyr Askaruly:** Methodology. **Kainaubek Toshtay:** Formal analysis. **Seitkhan Azat:** Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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