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MXenes FOR SUSTAINABLE ENERGY: ADVANCES IN SYNTHESIS, ENERGY STORAGE & HYDROGEN PRODUCTION

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ABSTRACT

MXenes are two-dimensional transition metal carbides, nitrides and carbonitrides that can be synthesized by selectively etching the A element from MAX phase precursors. Properties and potential uses of MXenes include hydrophilicity and high electrical conductivity as well as other properties that can be controlled by surface functionalization for uses in hydrogen and other energy applications. This review cites nine publications, seven review articles and two original research articles. Conventional MXene synthesis techniques involve potentially hazardous and environmentally unfriendly fluorine-based chemicals, such as hydrofluoric acid. Green synthesis approaches for MXenes include electrochemical, molten salt, ionic liquid, and deep eutectic solvent techniques and chemical vapor deposition. Other potential uses and properties of MXenes include supercapacitors with volumetric capacitances up to 1500 F cm−3 and lithium-ion battery anode materials with capacities over 1000 mAh g−1, though testing conditions differ. One review cites use of plant extracts to synthesize MXenes. Other knowledge gaps include water instability and restacking of MXene layers and a lack of information on MXene yields. Suggested areas for future research include studies comparing conventional and green MXene synthesis methods and efforts to standardize testing and reporting methods for MXene stability and yields.

Keywords: MXene; green synthesis; energy storage; batteries; supercapacitors; hydrogen evolution reaction

INTRODUCTION

The growing demand for clean energy has increased the need for materials that can store energy efficiently and help in water-splitting reactions. Two-dimensional (2D) materials are useful for these applications because they have a large surface area and allow ions to move over short distances. These properties make them suitable for

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energy storage and other energy-related applications (Ampong et al., 2023). MXenes are a newer group of 2D materials that were discovered in 2011 (Bhat et al., 2021).MXenes have the general chemical formula $M_{n+1}X_nT_x$, where M represents an early transition metal, X represents carbon and/or nitrogen, and n usually has a value from 1 to 3. T_x represents the surface functional groups, such as –OH, –O and –F, present on the MXene surface (Kahkesh & Yeganeh, 2026; Mubeen et al., 2024). MXenes are generally prepared from a group of materials called MAX phases, which have the general formula $M_{n+1}AX_n$. In this formula, A usually represents an element from Group 13 or Group 14 of the periodic table. The first MXene, $Ti_3C_2T_x$, was prepared by removing the aluminium layer from Ti_3AlC_2 using hydrofluoric acid (HF). This process is known as etching (Ampong et al., 2023; Mubeen et al., 2024).At present, different MXene compositions have been reported or predicted. The reported number varies from approximately 20 to more than 70, depending on whether only experimentally prepared MXenes or predicted compositions are considered (Ampong et al., 2023; Bhat et al., 2021; Kahkesh & Yeganeh, 2026).

HF-based etching is widely used for MXene synthesis because it is effective and provides good control over the etching process. Most of the MXenes reported in research have been prepared using HF-based methods (Xu et al., 2022). However, hydrofluoric acid is highly corrosive and dangerous to handle. Its disposal can also cause environmental problems. In addition, the presence of fluorine-containing surface groups may limit the use of MXenes in certain applications (Kahkesh & Yeganeh, 2026; Xu et al., 2022). To overcome these limitations, researchers are exploring green synthesis methods that aim to reduce the use of hazardous chemicals, maintain control over the synthesis process, and obtain MXenes with suitable surface functional groups (Kim et al., 2025).

The demand for energy storage is increasing because of the growing use of electric vehicles and renewable energy sources. Over the past few decades, the energy density of lithium-ion batteries has increased from approximately 90 to 300 Wh kg^{-1}. However, challenges related to cost, battery life and safety still need to be addressed to develop better energy storage systems (Kim et al., 2025).

Hydrogen is also considered a clean energy carrier, and producing it using renewable energy sources is an important step towards reducing carbon emissions (Mubeen et al., 2024). Platinum (Pt) is widely used as a catalyst for the hydrogen evolution reaction (HER). However, its high cost, limited availability and possible degradation under acidic conditions restrict its large-scale use (Mubeen et al., 2024).

To overcome these limitations, researchers have investigated other materials, including transition-metal dichalcogenides such as molybdenum disulfide (MoS_2) and tungsten diselenide (WSe_2). Although these materials show potential, their catalytic performance can be limited by the small number of active sites and slow reaction rates (Mubeen et al., 2024). MXenes have gained considerable interest in recent years due to their promising properties, such as high electrical conductivity, a large surface area and the flexibility to modify their surface chemistry

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according to different application requirements (Mubeen et al., 2024; Kannan et al., 2020). Despite these advantages, their practical use is still limited by several challenges, including the use of hazardous chemicals during synthesis, stability issues and variations in the results reported in different studies.

MXene Structure and Properties

MXenes have a layered structure that originates from their parent MAX-phase materials. In MAX phases, layers of transition metal atoms (M) are separated by A-group elements, while carbon or nitrogen atoms (X) are present between the metal atoms. During the synthesis of MXenes, the A-layers are selectively removed through an etching process. This results in the formation of thin, layered materials with the general chemical formula Mn+1XnTx. In this formula, Tx represents the functional groups attached to the MXene surface. These functional groups may be distributed unevenly across the surface. Therefore, theoretical models that consider a uniform distribution of surface groups may not accurately describe the actual MXene structure (Venkateshalu et al., 2020; Xu et al., 2022).

Surface functional groups have a significant influence on the physical and chemical properties of MXenes. They increase the interaction of MXenes with water, making them hydrophilic and suitable for processing in aqueous solutions (Mubeen et al., 2024). Their electrical behaviour also varies depending on their chemical composition. For instance, $Ti_3C_2T_x$ generally shows metallic characteristics, whereas Mo_2CT_x and $Mo_2TiC_2T_x$ have been reported to exhibit semiconducting behaviour (Bhat et al., 2021).

Surface terminations also influence the movement of lithium ions through MXene layers. Oxygen-terminated MXenes provide a relatively low energy barrier of approximately 0.2 eV for Li^+ migration compared with fluorine-terminated surfaces. This allows lithium ions to move more easily, making these materials promising candidates for battery applications (Kim et al., 2025). Additionally, some fluorine-containing surface groups can be removed during the washing process, resulting in changes to the surface composition of MXenes (Bhat et al., 2021).

Another important structural feature is the interlayer spacing, which refers to the distance between two neighbouring MXene layers. This spacing plays an important role in ion storage and transport because it determines how easily ions can enter, move through and exit the layered structure. Yamada (2024) reported a reflection corresponding to an interlayer spacing of 36.1 Å in Mo2C paper, which was attributed to the presence of retained tetrabutylammonium cations between the layers. Similarly, Mubeen et al. (2024) observed that the interlayer distance of Ti2CTx increased from 9 Å to 12.5 Å after sodium-ion (Na+) intercalation. This expansion creates more space between the layers and can help ions move through the material during electrochemical processes.

Oxidation is one of the major problems affecting the stability of MXenes, especially $Ti_3C_2T_x$ in aqueous solutions. Bhat et al. (2021) reported that when an aqueous suspension of $Ti_3C_2T_x$ was stored in open containers, its degradation reached 42% after

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5 days, 85% after 10 days, and 100% after 15 days. During this process, titanium dioxide (TiO_2) was formed. To improve stability, sodium L-ascorbate was used as a protective agent, which helped maintain the stability of colloidal $Ti_3C_2T_x$ for up to six months. Storage under frozen conditions provided further improvement in stability. The same study also reported that $Ti_3C_2T_x$ remained stable at temperatures up to 1200 °C under argon or hydrogen atmospheres (Bhat et al., 2021).

MXenes also show interesting optical and mechanical properties that make them useful for different technological applications. According to Bhat et al. (2021), oxygen-terminated Ti_2C has a predicted optical band gap of 0.9 eV. Several MXenes with different surface groups have narrow band gaps, which may need to be adjusted to improve their performance in optoelectronic devices. Xu et al. (2022) reported that theoretical calculations showed high elastic moduli along the basal planes of Ti_2CT_x, $Ti_3C_2T_x$, and Ta_2CT_x. These values were comparable to those of their parent MAX-phase materials. However, the mechanical properties of MXene films can vary depending on their composition and preparation method. Therefore, a single general value cannot be used to represent all MXene films.

The electrical properties of MXenes also depend on their chemical composition and surface terminations. For example, $Ti_3C_2T_x$ generally shows metallic behaviour, whereas some molybdenum-based MXenes exhibit semiconducting properties (Bhat et al., 2021). Oxidation can reduce the electrical conductivity of MXenes, making their stability an important factor when selecting them for practical applications (Mubeen et al., 2024). MXenes can also be processed into water-based inks and used to print conductive patterns. This shows that they combine good electrical conductivity with easy processing, making them promising materials for flexible electronics and other advanced applications (Bhat et al., 2021).

Conventional Synthesis Methods

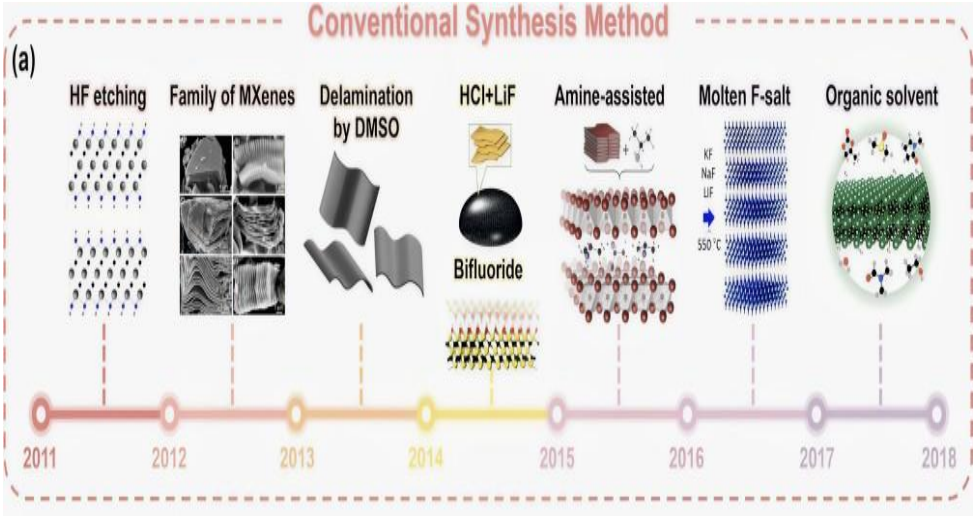
The conventional method for synthesizing MXenes involves removing the A layer from a MAX phase using hydrofluoric acid (HF). Naguib et al. used 50 wt% HF at room temperature for 2 hours to etch Ti_3AlC_2. (Alhabeb et al. Mubeen et al. 2024) reported that using 30 wt% HF could also produce an accordion-like MXene structure similar to the one obtained with 50 wt% HF. However, lower HF concentrations, such as 5 wt% and 10 wt%, were not able to produce the same structural changes. After the etching process, tetramethylammonium hydroxide (TMAOH) can be added to separate the stacked MXene layers. This separation process is known as delamination (Mubeen et al., 2024). To reduce the direct use of concentrated hydrofluoric acid (HF), researchers have also explored an alternative approach using fluoride salts along with hydrochloric acid (HCl). During the reaction, these chemicals generate HF, which helps remove the aluminium layer from the MAX phase. For example, a mixture of lithium fluoride (LiF) and HCl has been used to etch Ti_3AlC_2 at 35 °C for 24 hours to obtain MXene (Bhat et al., 2021). Similarly, NaF/HCl was found to etch Cr_2AlC more quickly and produce a higher yield than the other fluoride salts tested (Mubeen et al., 2024). According to Kim et al. (2025), hydrothermal etching may leave aluminium hydroxide impurities in the

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final product. These impurities can reduce the yield, so additional acid washing may be required.

The preparation of Mo_2CT_x using a conventional synthesis approach. In this study, Mo_2C was first heated with gallium at 850 °C for 48 hours to form Mo_2Ga_2C. The gallium layer was then removed using hydrochloric acid (HCl). After this step, the material was treated with 49% hydrofluoric acid (HF) at 55 °C for 160 hours to obtain Mo_2CT_x. The resulting material was further treated with TBAOH to separate the MXene layers. After centrifugation, vacuum filtration was carried out to obtain a thin Mo_2C paper with an approximate thickness of 16 µm (Yamada, 2024). In another study, Venkateshalu et al. (2020) mixed vanadium (V) and aluminium nitride (AlN) using ball milling for 26 hours. The mixture was then heated at 1100 °C under an argon atmosphere to prepare V_2AlN. This material was etched using LiF/HCl to obtain the MXene. However, ICP-OES analysis showed that the final product still contained 9.26% aluminium.

Overall, conventional HF-based methods are widely used because they provide good control over the synthesis process and can produce MXenes with different compositions and high yields. Kahkesh and Yeganeh (2026) described HF etching as a well-established method with good selectivity. However, the main disadvantages are the hazardous nature of HF and the difficulties associated with chemical waste disposal. Using fluoride salts with HCl can reduce the need to handle concentrated HF directly while maintaining effective etching. However, these methods still involve fluoride-containing chemicals, so proper washing, waste disposal and laboratory safety precautions remain important.



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Fig. 1 (a) Timeline illustrating the progress of Conventional Synthesis Methods, highlighting key advancements over time. Reproduced with permission from Ref [39, 65]. Copyright 2011, 2016, John Wiley & Sons, Inc. Reproduced with permission from Ref [49, 74, 75]. Copyright 2012, 2017, 2014, American Chemical Society. Reproduced with permission from Ref [59]. Copyright 2014, Springer Nature. Reproduced with permission from Ref [66]. Copyright 2016, Royal Society of Chemistry. Reproduced with permission from Ref [73]. Copyright 2020, Elsevier.

Green Synthesis Methods

Green synthesis aims to prepare MXenes by reducing the use of hazardous chemicals, lowering waste generation and minimizing energy consumption. The main goal is to develop a safer and more environmentally friendly synthesis process while maintaining the quality of the final material. According to Kahkesh and Yeganeh (2026), green synthesis methods can be evaluated based on chemical safety, scalability, energy requirements, environmental impact, surface terminations and suitability for different applications. Kim et al. (2025) also highlighted the importance of developing greener synthesis methods to increase the use of MXenes in batteries.

Electrochemical Etching

Electrochemical etching is one approach used to prepare MXenes. In this method, aluminium is removed from a Ti_2AlC electrode by applying an electrical potential in 1 M diluted HCl. Sun et al. (2017), as cited by Mubeen et al. (2024), used a potential of +0.6 V for 24 hours to carry out the etching process. This method provides better control over the etching rate and selectivity, and the reaction can be monitored during synthesis. However, it requires specialised equipment and may be difficult to scale up for large-scale production (Kahkesh & Yeganeh, 2026).

Molten Salt Etching

Molten-salt etching is another method for synthesizing MXenes. It involves using molten salts to remove the A layer from a MAX phase. For example, Ti_3ZnC_2 can be converted into $Ti_3C_2Cl_2$ using molten $ZnCl_2$ (Ampong et al., 2023; Kahkesh & Yeganeh, 2026). However, this method requires high temperatures, often above 750 °C, and the reaction may continue for up to 24 hours. Therefore, its high energy requirements are an important limitation (Kim et al., 2025).

Ionic liquid Etching

Ionic-liquid etching has also been investigated as an alternative to conventional HF-based methods. Husmann et al. (2020), as cited by Mubeen et al. (2024), used a mixture of ionic liquid and water in a 1:3 ratio at 80 °C for 20 hours to remove aluminium completely from Ti_3AlC_2 and Ti_2AlC. In this method, fluorine-containing groups were introduced from BF_4^- and PF_6^- anions rather than from free fluoride ions. Although this approach offers an alternative way to control the etching process, the environmental impact and safety of the ionic liquids must also be considered.

DES Etching

Deep eutectic solvent (DES) etching is another approach explored for MXene preparation. Wu et al. (2020), as cited by Mubeen et al. (2024), used a mixture of choline chloride, oxalic acid and ammonium

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fluoride (NH_4F) to prepare Ti_3C_2. The reported purity reached up to 98%. This method is of interest because deep eutectic solvents can provide an alternative reaction medium. However, the use of ammonium fluoride means that the process cannot be considered completely free of hazardous chemicals.

Alkaline Etching

Alkaline etching uses alkaline chemicals instead of conventional concentrated HF. Kahkesh and Yeganeh (2026) reported that treatment with NaOH at 270 °C for 12 hours produced MXene with approximately 92% purity and oxygen-rich surface terminations. The surface terminations are important because they influence the chemical properties and potential applications of MXenes. However, the high temperature and long reaction time may increase energy consumption.

OTHER METHODS

Another approach is photo-Fenton etching, which combines chemical reactions with ultraviolet (UV) light. According to Kahkesh and Yeganeh (2026), this method uses Fe^{3+} ions, sodium oxalate and hydrogen peroxide (H_2O_2) under UV irradiation. After approximately 10 hours, the reported purity reached about 95%. This technique offers another way to prepare MXenes without depending completely on conventional etching methods. However, the chemicals used in the process and the energy needed for UV treatment should also be considered when studying its environmental impact. Different alternative techniques are now being explored to reduce the use of highly concentrated hydrofluoric acid (HF) in MXene preparation. However, using an alternative method does not always mean that the process is completely environmentally friendly. Some techniques require high temperatures, special instruments or chemicals that may cause environmental and safety concerns. Therefore, a suitable synthesis method should be selected by considering several factors, including the purity of the final product, chemical safety, energy requirements, waste production and overall preparation cost. It is equally important to ensure that the prepared MXenes have the required properties for battery and other energy-storage applications.

Bottom-up synthesis is another method used to prepare MXene-based materials. In this approach, the material is developed by combining smaller building blocks to form the required structure. It is different from the conventional top-down method, where MXenes are obtained by removing the aluminium (A) layer from a MAX phase. Thus, bottom-up synthesis provides an alternative route for preparing two-dimensional materials without using the traditional MAX-phase etching process (Mubeen et al., 2024; Kim et al., 2025). One example is chemical vapour deposition (CVD), in which gaseous chemicals react under controlled conditions to form a material on a suitable surface. Mubeen et al. (2024) reported the growth of Mo_2C on copper/molybdenum (Cu/Mo) foil using hydrogen (H_2) and methane (CH_4). The resulting sheets had lateral dimensions greater than 100 µm. Similarly, Talapin et al. prepared Ti_2CCl_2 using titanium, graphite and titanium tetrachloride ($TiCl_4$), without using a MAX-phase precursor (Kim et al., 2025).

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CVD offers advantages such as high purity and better control over the structure of the prepared material. However, it generally requires high temperatures and considerable energy consumption. Kahkesh and Yeganeh (2026) gave CVD a score of 1 out of 5 for energy demand, indicating poor performance in this category. Although Mubeen et al. (2024) discussed its scalability, the practical ability to produce MXenes on a large scale must also be considered in relation to energy requirements and production costs.

Biogenic exfoliation is another approach that uses plant extracts or extracts obtained from waste materials to assist in separating layered materials into thinner sheets. Kahkesh and Yeganeh (2026) reported a study in which coffee-waste and gallnut extracts were used with bath sonication to exfoliate graphite, hexagonal boron nitride (h-BN) and HF-etched Ti_3AlC_2. This approach is interesting because plant-derived and waste-derived extracts may provide a more sustainable alternative for certain processing steps.

However, the exact roles of individual plant compounds in the exfoliation process are not yet clearly established in the papers reviewed. Furthermore, the research papers considered here do not report a direct experimental study of MXene synthesis using plant extracts. Therefore, results from the plant-mediated synthesis of metal nanoparticles cannot be directly applied to MXenes, as their structures and synthesis requirements are different.

Effect of Synthesis Conditions on MXene Properties : The synthesis conditions play an important role in determining the quality, structure and yield of MXenes. According to Kim et al. (2025), excessively high etching temperatures or prolonged reaction times can increase structural defects and reduce the yield of delaminated MXene. Therefore, the reaction conditions must be carefully controlled to obtain good-quality material.

Microwave-assisted etching is another approach that can reduce synthesis time. Kim et al. (2025) reported that microwave-assisted NaOH etching produced few-layer MXenes in approximately 30 minutes. However, the yield was below 10%, which limits the practical usefulness of this method. This finding shows that reducing synthesis time does not necessarily result in a higher product yield. Further optimisation is needed to improve the efficiency of the process while maintaining the desired structural and chemical properties of MXenes.

Applications in Energy Storage and Hydrogen Production

Supercapacitors

Supercapacitors are energy storage devices that can charge and discharge quickly. They provide high power and have a long cycle life, making them useful for energy storage applications (Venkateshalu et al., 2020). MXenes are suitable materials for supercapacitors because they have high electrical conductivity and can also store charge through pseudocapacitance. In acidic electrolytes, hydronium ions can reversibly interact with oxygen-containing surface groups of MXenes, helping to store electrical charge (Mubeen et al., 2024).

For example, binder-free $Ti_3C_2T_x$ clay films showed a volumetric capacitance of approximately 900 F cm^{-3} at a scan rate of 2 mV s^{-1} in H_2SO_4 electrolyte (Xu et al., 2022). Similarly, Venkateshalu et al. (2020) reported that a V_2NT_x electrode achieved a

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specific capacitance of 112.8 F g^{-1} at a current density of 1.85 mA cm^{-2} in 3.5 M KOH. It also retained 96% of its capacitance after 10,000 charge–discharge cycles at 5 mA cm^{-2}.

The researchers also developed an asymmetric supercapacitor using V_2NT_x and Mn_3O_4 nanowalls. This device operated within a voltage window of 1.8 V and delivered a specific capacitance of 25.3 F g^{-1} at 1.85 mA cm^{-2}. These results show that MXenes have good potential for supercapacitor applications because of their charge-storage ability and cycling stability. However, the reported capacitance values were measured using different methods of normalisation, so they cannot be directly compared.

Lithium-Ion and Sodium-Ion Batteries

MXenes are promising materials for lithium-ion and sodium-ion batteries because they can store ions between their layers. In lithium-ion batteries, lithium ions enter the MXene structure during charging and leave it during discharging. This process is known as intercalation. For example, lithium storage in Ti_3C_2 can be represented as $Ti_3C_2 + 2Li \rightarrow Ti_3C_2Li_2$ (Mubeen et al., 2024).

$Ti_3C_2T_x$ showed a reversible capacity of 220 mAh g^{-1} at a C/25 rate (Mubeen et al., 2024). In another study, a MoS_2/Ti_3C_2 composite used as an anode material achieved a capacity of 1200 mAh g^{-1} and maintained 600 mAh g^{-1} even at a high current density of 20 A g^{-1}. Among the anode materials compared in their review, Mubeen et al. (2024) reported that this composite showed the best performance.

MXene-based composites have also shown good results in sodium-ion batteries. For example, MoS_2/Ti_2CT_x delivered a capacity of 250.9 mAh g^{-1} at a current density of 100 mA g^{-1} after 100 cycles, with 88% capacity retention (Mubeen et al., 2024).

Despite these advantages, some challenges still limit the performance of MXene-based batteries. These include the restacking of MXene layers, low initial coulombic efficiency and lower-than-theoretical storage capacity. Restacking reduces the available surface area and makes it difficult for ions to move between the layers. Xu et al. (2022) reported that V_2CT_x has a theoretical capacity of 940 mAh g^{-1}, whereas its measured capacity was only 252 mAh g^{-1}. Therefore, further research is needed to improve the structure and electrochemical performance of MXene-based electrodes for battery applications.

Lithium–Sulfur Batteries

Lithium–sulfur batteries are promising energy storage devices because they have a high theoretical capacity of 1675 mAh g^{-1}. However, their performance is limited by the low electrical conductivity of sulfur and the polysulfide shuttle effect, in which soluble polysulfides move between the electrodes and reduce battery performance (Xu et al., 2022).

MXenes can help overcome these problems because their surfaces interact with polysulfides and help prevent them from moving freely between the electrodes. In particular, titanium-based MXenes can form Ti–S bonds with polysulfides, while sulfur can replace –OH groups present on the MXene surface. These interactions help improve polysulfide retention and support better battery performance (Xu et al., 2022).

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Metal–Air and Transient Batteries

MXenes are also being studied for metal–air batteries and biodegradable batteries because of their useful electrical and catalytic properties. For example, a catalyst made from Mn_3O_4 and $Ti_3C_2T_x$ was tested in a zinc–air battery. It achieved a power density of 150 mW cm^{-2} and an open-circuit voltage of 1.37 V. The battery also showed stable performance for 100 hours (Mubeen et al., 2024).

In another study, Yamada (2024) developed a biodegradable magnesium–Mo_2C battery. The battery showed an open-circuit voltage of 1.6 V and an operating voltage of 1.4 V at a current density of 0.1 mA cm^{-2}. It delivered a capacity of 0.57 mAh cm^{-2} and a maximum power density of 0.92 mW cm^{-2}. The battery gradually degraded in a phosphate-buffered saline (PBS) solution of 10 mM at 37 °C and had broken down by day 123.

Yamada (2024) suggested that Mo_2C might slow down the hydrogen evolution reaction in an alkaline solution. However, this reaction was not measured directly in the study. Therefore, further experiments are needed to confirm the role of Mo_2C in controlling hydrogen production and to understand its effect on battery performance.

These findings indicate that MXene-based materials have potential applications in zinc–air batteries and biodegradable energy storage devices. However, more research is needed to improve their performance and understand their behaviour under different operating conditions.

Hydrogen Evolution and Photocatalysis

The hydrogen evolution reaction (HER) is an important process for producing hydrogen. It involves three main steps: Volmer, Heyrovsky and Tafel (Mubeen et al., 2024). A good catalyst should have a hydrogen adsorption free energy close to zero, allowing hydrogen to bind and release easily (Mubeen et al., 2024). According to Kannan et al. (2020), the calculated values are approximately 0.048 eV for Mo_2CT_x and 0.358 eV for Ti_2CT_x. The reported overpotential at 10 mA cm^{-2} is 283 mV for Mo_2CT_x and 609 mV for Ti_2CT_x (Bhat et al., 2021). Kannan et al. (2020) reported a lower value of 189 mV for Mo_2CT_x under similar conditions. This difference is discussed in Section 6. $Ti_4N_3T_x$ showed an overpotential of about 300 mV, while a Pt/$Ti_3C_2T_x$ hybrid achieved 67.8 mV, close to the 64.2 mV reported for commercial Pt/C (Bhat et al., 2021; Mubeen et al., 2024).

In photocatalysis, MXenes help capture electrons produced by light and improve hydrogen production. The reported hydrogen production rates reached 17,070 µmol h^{-1} g^{-1} for Ti_3C_2@Au@CdS and 2407 µmol g^{-1} h^{-1} for a CdS/Ti_3C_2 heterojunction (Mubeen et al., 2024; Bhat et al., 2021). However, these results cannot be directly compared because the studies used different light sources, catalyst amounts and filters.

MXenes have also been studied for potassium-, zinc-, aluminium- and magnesium-ion batteries. One zinc-ion battery electrode achieved approximately 240 mAh g^{-1} at 2 A g^{-1} after 5000 cycles (Xu et al., 2022). However, further research is needed because testing conditions vary between studies. Mubeen et al. (2024) also noted that magnesium–air and aluminium–air batteries were not covered in the studies they reviewed.

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For micro-supercapacitors, directly printed MXene inks without additives achieved a volumetric capacitance of 562 F cm^{-3}. Sodium-ascorbate-stabilised inks showed a higher value of 720.7 F cm^{-3} after 80 days of storage (Bhat et al., 2021). These inks can be printed on paper and polypropylene, making them useful for flexible and temporary electronic devices.

Challenges and Research Gaps

Despite the growing interest in green synthesis of MXenes, several challenges still limit their development and practical use. One of the major difficulties is producing MXenes on a large scale while maintaining consistent quality, purity and reproducibility. Different synthesis conditions can also affect the structure and properties of the final material (Kahkesh & Yeganeh, 2026; Kim et al., 2025). Another important concern is the poor stability of MXenes in aqueous environments. When exposed to water and oxygen for a long time, they may undergo oxidation, which can reduce their electrical conductivity and affect their overall performance (Bhat et al., 2021; Xu et al., 2022). The safety of MXenes also needs further investigation. More experimental studies are required to understand their toxicity, biodegradation and possible effects on living organisms before using them in biomedical and environmental applications (Kahkesh & Yeganeh, 2026). In addition, the exact catalytic mechanisms of MXene-based nanocomposites are not yet completely understood. A better understanding of the interactions between MXenes and other materials is needed to explain their catalytic behaviour (Bhat et al., 2021). Some theoretically predicted properties, including topological insulating behaviour and ferromagnetism, also need proper experimental verification. Overall, further research should focus on developing reliable synthesis techniques, improving oxidation resistance, evaluating material safety and confirming the predicted properties of MXenes. Addressing these issues will help bridge the gap between laboratory research and their practical applications.

Future Perspectives

The following points suggest possible directions for future research on MXenes. One important area is the development of fluoride-free synthesis techniques that can provide better control over surface functional groups and improve the final product yield. Methods such as molten-salt synthesis and electrochemical etching could be explored as possible alternatives for large-scale MXene production. Future studies should also compare green synthesis techniques with conventional HF-based methods using the same starting materials. This would help researchers understand the differences in material quality, structure and overall performance. In addition, more research is required to identify the active compounds present in plant extracts and understand their role in the reduction, stabilisation and surface modification of MXenes. Another important aspect is the long-term stability of MXene materials. Standard testing procedures should be introduced to monitor changes in their electrical conductivity and energy-storage capacity during storage and use. Life-cycle assessment and cost evaluation are also necessary to determine whether green synthesis methods are truly more economical and environmentally friendly than conventional techniques. Advanced characterisation techniques can

provide a better understanding of MXene behaviour during practical applications. In-situ and operando studies during battery charging and discharging or hydrogen evolution reactions may help explain how surface functional groups influence their performance. Combining techniques such as X-ray Photoelectron Spectroscopy (XPS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) would also provide useful information about the surface chemistry and overall elemental composition of these materials. Finally, greater attention should be given to the safety of MXenes, especially when they are used in biomedical and environmental applications. Standard toxicity and biodegradation studies are needed to understand their effects on living organisms and the environment. Such investigations will be particularly important for developing biodegradable and temporary electronic devices.

CONCLUSION

Although different fluoride-free synthesis approaches are being explored as safer alternatives to conventional HF-based methods, several challenges still need to be addressed. These include improving the synthesis yield, maintaining material purity and enhancing long-term stability. The use of plant extracts for the green synthesis or modification of MXenes is also an interesting research area, but it requires further experimental investigation to establish its effectiveness. The electrochemical performance of MXenes can also change depending on the experimental conditions used, which makes it difficult to compare results from different studies directly. Therefore, future research should give importance to safer and more sustainable synthesis techniques, along with uniform testing procedures and proper reporting of experimental results. These improvements will help researchers understand MXenes more clearly and support their development for practical energy-storage and hydrogen-production applications (Bhat et al., 2021; Ampong et al., 2023; Bi et al., 2024).

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