



Mxenes: Next-Generation 2D Platforms for Sustainable Energy and Environmental Remediation

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Abstract: MXenes, an increasingly diverse class of two-dimensional (2D) transition-metal carbides, nitrides, and carbonitrides, have become influential materials for sustainable energy systems and environmental clean-up technologies. Since first being reported in 2011, over 30 MXene compositions have been produced, combining high metallic conductivity (up to $15,100 \text{ S cm}^{-1}$), hydrophilic surface terminations, and adjustable interlayer spacing features that make them strong candidates for tackling major sustainability needs. This review progress in MXene research from 2020 to 2025, highlighting developments across environmental sensing, water purification, electrocatalysis, and electrochemical energy storage. It also critically discusses new composite designs, links between performance and structure, and synthesis approaches, while addressing persistent obstacles including broader environmental considerations, manufacturing at scale, and oxidation resistance. As decarbonization initiatives speed up and water-quality regulations become more stringent, MXenes represent a promising materials platform for advancing sustainable development via versatile clean-energy and environmental applications.

Keywords: MXenes, 2D Materials, Energy Storage, Environmental Remediation, Sustainability, Electrocatalysis.

1. Introduction

MXenes attracted significant interest in 2011 after Drexel University researchers successfully synthesized a new class of two-dimensional (2D) materials. This advance was achieved by selectively etching away the A-layer from MAX phases [1, 2]. The initial compound, Ti_3C_2 , was obtained by etching Ti_3AlC_2 with hydrofluoric acid, which opened the door to a broad family of 2D transition-metal nitrides, carbonitrides, and carbides. Following the first discovery of MXenes, over 30 of them have been experimentally reported, and theoretical studies indicate that more than 100 compositions are possible [3-5]. Scientific attention to MXenes has expanded remarkably, rising from fewer than 50 papers in 2012 to more than 3,000 by 2024, based on Web of Science data [6]. The h-index of this journal now stands at 156, supported by more than 180,000 citations overall [7], highlighting the significant impact of MXene research within materials science. A key driver of this developing advancement is based on the inherent tunability and structural variety of MXenes. In contrast to graphene, which typically needs chemical

functionalization, MXenes can be tailored directly through their composition (M, A, and X elements) and surface terminations (T_x), providing substantial flexibility for designing materials for specific applications [8]. These characteristics have driven the broad adoption of MXenes across many fields, such as electronics, energy storage, environmental technologies, and catalysis [9].

Owing to their distinct set of properties MXenes are notable in the recent years. Among those $\text{Ti}_3\text{C}_2\text{T}_x$ films exhibit exceptionally high electrical conductivity, typically ranging from about 6,000 to more than 15,000 S cm^{-1} , comparing these values with those of metals, MXenes provide an added advantage of being compatible with solution-based processing [10]. This electrical conductivity arises from delocalized d-electrons within the transition-metal layers, which produce metallic band structures and a high density of electronic states near the Fermi level. Another important characteristic of MXenes is their hydrophilic nature, due to the presence of polar surface functional groups such as -F, -OH, and -O. These surface properties promote the formation of stable dispersions in water, often

reaching concentrations above 50 mg mL⁻¹ [11]. This helps in the incorporation of large-scale manufacturing and straightforward processing. Moreover, upon changing the synthesis treatments or using targeted post-treatments, surface terminations can be tuned, and influence some of the properties like the chemical reactivity, interlayer spacing (0.98-1.40 nm), and work function (4.1-6.2 eV) [12, 13]. MXenes have a layered architecture that enables adjustment of the spacing between layers, and these interlayer regions can accommodate different ions and molecules, which makes them valuable for various applications like ion transport, nanocomposite, and filtration [14]. In addition, these materials usually exhibit a negative zeta potential (-30 to -45 mV), which improves colloidal stability and promotes interactions with positively charged species [15]. MXenes have also shown strong pseudocapacitive properties, along with rapid charge storage and maintaining high energy density. This performance stems from fast surface redox reactions and ion intercalation within their layered structure. Volumetric capacitances for MXenes have been reported to be about 1500 F cm⁻³, surpassing many conventional supercapacitor materials [16, 17].

As carbon emissions climb and freshwater resources become increasingly limited, new material innovations are essential. In 2023, global CO₂ emissions reached a higher rate of 37.4 billion tonnes, underscoring the need for cleaner technologies and the push to meet net-zero goals by 2050 [18]. Meanwhile, more than 2 billion people still has a limited availability of drinking water, a problem worsened by industrial pollution and climate change [19]. The IEA's net-zero roadmap shows the crucial role of materials that enable carbon capture, energy storage, and renewable power [20]. MXenes are being recognized as one of the promising options for various applications in supercapacitors and high-performance batteries, efficient CO₂ and hydrogen electrocatalysis, and energy conversion technologies as regulations become more stringent [21]. Under the European Union's Water Framework Directive, permissible concentrations of heavy metals are now capped at levels as low as 5 µg L⁻¹ for cadmium and 10 µg L⁻¹ for lead [22]. Likewise, recent revisions from the US EPA and China's "Water Ten Plan" emphasize the need for advanced treatment technologies that can eliminate the trace concentrations of materials in the pollutant [23]. MXenes, owing to their large surface area and adaptable chemistry, offer promising approaches for addressing the environmental challenges. In addition to performance, sustainability is increasingly central, as materials circularity underscores responsible sourcing, recyclability, and cleaner production processes [24]. MXenes, derived from the abundant MAX phases, show promise in this field, but there is an increasing need for environmentally friendly, fluoride-free synthesis methods to lessen ecological impact.

1.2 Scope and Aims of This Review

This review offers a thorough summary of recent progress in MXene from 2020-2025, emphasizing its environment and energy related applications. It explores five key areas:

- Progress in synthesis and surface modification methods, including new etching techniques and post-treatments.
- Utilization of MXenes in energy storage technologies, including batteries and supercapacitors, as well as their catalytic roles in hydrogen production and carbon dioxide conversion.
- Applications in environmental remediation, including removal of heavy metals, organic pollutants, and salts, as well as air purification and antimicrobial action.
- Development of MXene-based composites and hybrid systems that improve performance through material synergy.
- Ongoing challenges related to oxidation, synthesis scalability, safety, and data standardization, along with new research areas like twisted-bilayer MXenes, MXene quantum dots, and machine-learning-aided design.

This review has focused only on peer-reviewed articles published within the specified timeframe. It prioritizes mechanistic insight, scalability, and quantitative results to support researchers in converting MXene technologies to industrial applications. The goal of this article is to update and extend prior reviews by underscoring ongoing discussions, presenting recent findings, and outlining future directions for integrating MXenes into broader efforts toward clean energy and environmental health.

2. Review Methodology

2.1 Database Selection and Search Plan

A comprehensive search approach was used to collect pertinent studies on MXenes, with a focus on environmental applications and sustainable energy. Two primary sources were used for this review: the Web of Science Core Collection (Clarivate) and Scopus (Elsevier). The selection of these sources are based on their broad coverage of engineering and materials science, which are widely recognized for indexing most peer-reviewed research in this field [25].

The search used a structured approach consistent with PRISMA-ScR guidelines, ensuring a systematic and transparent screening process for sources [26]. Boolean operators were applied to build the search queries, and Medical Subject Headings (MeSH) were integrated with field-specific terms. Input

from experts and initial pilot searches helped refine the terminology.

2.2 Time Frame and Inclusion Standards

This review examines literature published from January 2020 to June 2025. This timeframe was selected based on the recent developments and the shift of MXenes from early exploratory research to industrial applications. The selected articles were evaluated using a modified Critical Appraisal Skills Programme (CASP) checklist tailored to data transparency, reproducibility, analytical rigour, enabling assessment of experimental design, and materials research [26].

2.3 Exclusion Parameters

Several types of studies have been omitted for this work, in order to maintain consistency and ensure relevance. These included papers not related to MXenes or those addressing only other 2D materials (e.g., graphene), unless such materials were incorporated into an MXene-based composite. Publications without sufficiently detailed methods or performance data were excluded, as were abstracts lacking accessible full-text versions. Duplicate records identified across multiple databases were removed to prevent redundancy, and studies focused solely on synthesis without linking it to practical applications were excluded. Furthermore, non-English articles without dependable translations were also excluded, due to overstated conclusions or methodological shortcomings. Lastly, preprints that had not yet been peer reviewed were also not considered.

2.4 PRISMA Workflow and Article Screening

The selection process followed the PRISMA framework. An initial search retrieved 2138 records from the selected databases. After removal of 1036 duplicate records, 1102 records remained for title and abstract screening. Of these, 695 records were excluded as irrelevant, leaving 407 full-text articles for eligibility assessment. After full-text review, 243 articles were excluded based on the predefined eligibility criteria. Ultimately, 164 articles were included in the qualitative review and the flow of this screening process is depicted in Figure S1.

2.5 Limitations and Bias Considerations

Even though this review followed a systematic process, we acknowledge a few limitations. One is publication bias, where studies with positive results are more likely to be published, and potentially overstating MXene performance. We also acknowledge language bias, as we only considered English publications, which may have resulted in the omission of essential findings from countries such as China or Russia. Database

limitations are another factor; some niche journals or preprint platforms might not be covered in the databases we selected. There is also a time related bias because studies that were published before 2020 were excluded even if they are still relevant to the review. Finally, location-based bias may mean that our findings are more focused on countries with established research systems or better access to publishing tools. To minimize potential biases, we conducted a comprehensive search and also manually reviewed the reference lists of key articles. In addition, to ensure that no relevant studies were missed, we consulted subject matter experts.

3. Synthesis, Structure & Surface Chemistry

3.1 MAX Phase Precursors and Crystal Framework

MXenes are derived from MAX phases from a family of layered materials, generally described by the formula $M_{n+1}AX_n$ ($n = 1-3$) as depicted in Figure 1. Here, M denotes an early transition metal such as niobium, vanadium, or titanium; A is usually a 13 and 14 group element, for example silicon or aluminium; and X refers to nitrogen, carbon, and sometimes a combination of both the elements [27]. These materials are generally made up of densely stacked metal layers separated by A elements planes, where the octahedral voids inside the metal layers are occupied by X atoms. Frequently used MAX phases for producing MXenes include Nb_2AlC , V_2AlC , Ti_2AlC , and Ti_3AlC_2 .

In the recent days, complex phases such as Cr_2TiAlC_2 and Mo_2TiAlC_2 have been developed, creating new opportunities owing to their diverse compositions and tunable properties [28]. In general, high-temperature solid-state synthesis are used to create MAX phases (about 1200-1600°C) using binary precursors or metal powders. Both the reaction temperature and duration strongly affect grain features and phase purity, which ultimately influence the quality of the resulting MXene. Research on MAX phases shows that particle size around 1-50 μm has a major impact on etching rate and the resulting MXene architecture [29].

3.2 Etching Methods: Traditional and Evolving Techniques

3.2.1 Conventional HF-Based Etching

The most commonly used etchant to obtain MXenes from MAX phases is hydrofluoric acid. In this process, the reaction selectively attacks the A layers and removes them through,



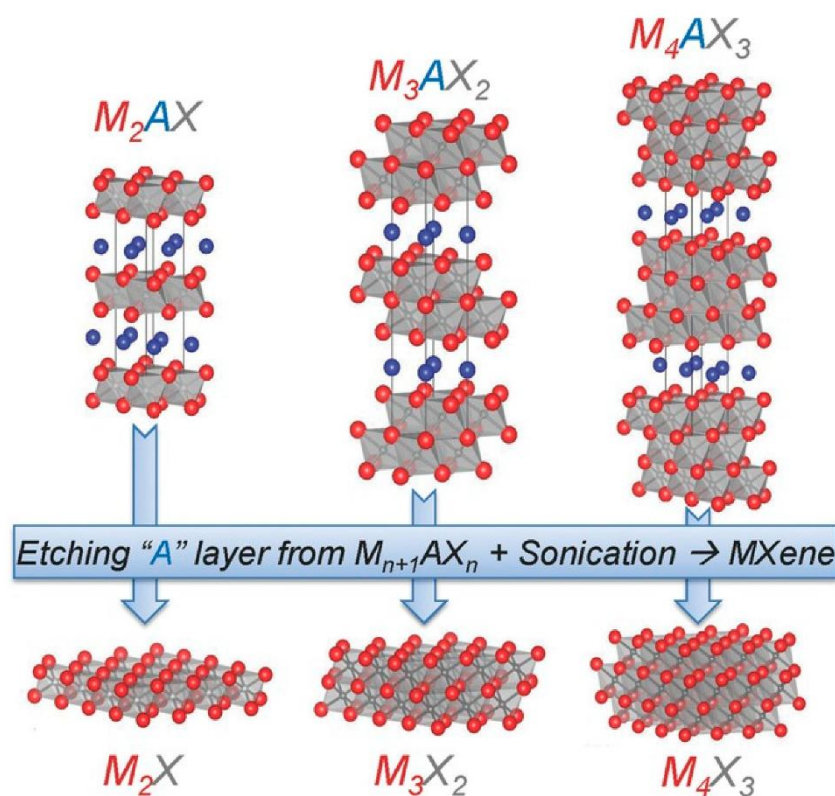
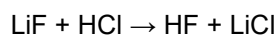


Figure 1. MXene phase structure and crystal framework [30].

Etching of MXenes are usually carried out at room temperature using hydrofluoric acid solutions of about 10%-50%, in a time period of 18 to 72 hours. A close control over reaction time and HF concentration and reaction time is needed: whereas too dilute solutions may fail to completely eliminate the A layer and overly concentrated HF can harm the MXene framework. For instance, Ti_3AlC_2 can be effectively etched in 10% HF within 24 hours, whereas V_2AlC typically needs about 20% HF because of the stronger bonding of group 5 transition [31, 32]. Regulating the temperature is equally important, since elevated temperatures (over 40°C) typically cause lower electrical performance and more defects.

3.2.2 Safer Etching via In-situ HF (LiF + HCl)

To reduce the risks of handling HF, a safer approach is carried out to produce HF in situ within the reaction medium by mixing LiF with HCl.



This method employs mixing different ratios of LiF:HCl from 1:1 to 1:3, using 6-12 M HCl for 24-48 hours at $35\text{-}60^\circ\text{C}$. Improved control over HF generation is provided by this method and also enables concurrent Li^+ intercalation, which facilitates subsequent delamination [33]. Compared with direct etching of materials by HF, MXenes obtained by this approach generally have larger flakes around $5\text{-}15\ \mu\text{m}$ with fewer surface imperfections. Moreover, Li^+ ions enhances delamination in solvents by expand the interlayer distance roughly from 0.98 nm to

about 1.3 nm. In situ XRD results indicate that etching and intercalation proceed at the same time, which helps in preserving the structure throughout the treatment [34].

3.2.3 High-Temperature Molten Salt Etching

Molten salt etching employs fluoride salts like KF, NaF, or LiF at high temperatures ($500\text{-}700^\circ\text{C}$) for the selective removal of A layers from MAX phases. During the initial process fluorides react to produce volatile AlF_3 , which is subsequently extracted under vacuum [35]. Investigation on recent studies shows that employing eutectic salt blends (e.g., KF, NaF, LiF) to reduce the operating temperature to around 450°C while still enabling selective etching [36]. In comparison with previous HF methods, this technique results in MXenes with fewer -F surface groups and more -O, and altering their electrochemical behavior [37]. This kind of etching technique enables ongoing production and eliminates liquid waste. However, reduced electrical performance is observed because exposure to high temperatures cause partial oxidation with the formation of defects.

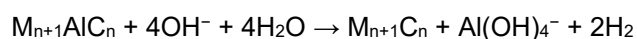
3.2.4 Electrochemical Etching

In this etching technique a MAX-phase electrode is subjected to anodic treatment in fluoride-containing electrolytes and the A element is selectively eliminated through electrochemical dissolution, when a voltage is applied. For regulating the proportions of different Mo-Ti MAX phases researchers have tuned the aluminium and carbon levels. Additional aluminium and

the inclusion of nickel promote the formation of intermediate alloys such as TiAl_3 and Ni_2Al_3 , which have lower melting points and thereby speeding up the process [38]. Rather than constant voltages applying pulsed voltages can minimize defects and enhance structural quality [39]. This etching method can be applied for selective etching in composite materials or in patterned structures, while also providing the suitability for use in aqueous environments and advantages of minimal waste.

3.2.5 Fluorine-Free Synthesis Approaches

As safety and environmental issues attract more attention, use of fluorine-free etching is increasing. Among the various method one of the methods relies on concentrated alkalis such as KOH or NaOH (20-40 M) in sealed, high-temperature conditions (270-350 °C). In this process, soluble $\text{Al}(\text{OH})_4^-$ complexes are formed by dissolving aluminium [15],



MXenes synthesised by this technique generally possess a higher density of surface -O and -OH terminations, which leads to increased pseudocapacitive characteristics and different electrochemical responses. In addition to this technique, alternative routes include plasma etching, hydrothermal treatment, and Lewis's acid etching. Lewis acidic molten salts (LAMS) are used by Lewis's acid etching technique to synthesize MXenes and related hybrid materials. Beyond improving safety, this strategy offers better control over surface chemistry and supports in situ formation of hybrids. While it remains an emerging technique, hydrothermal etching with KOH has shown promising potential. [40]. By applying thermal pre-treatment and allowing reaction to proceed for extended periods (up to 64 hours) can promote the formation of nanofiber. MXene PEDOT:PSS aerogels created using this approach have shown a specific capacitance of 20.96 F/g and maintained 72% of their performance after 1000 cycles [41]. A two stage plasma treatment with O_2 and N_2 improves the specific surface area, wettability, and pore architecture. The outcome of this technique results in enhanced electrochemical behavior and the modified MXene/CNF electrode reaches 162 F/g and maintains 124% capacitance after 10,000 cycles in a KOH electrolyte. An asymmetric device created using this material also achieved a strong stability over 5,000 cycles and exhibited 26.3 Wh/kg at 750 W/kg [42]. Although these fluorine-free approaches are still being refined, they offer potential for safer, more environmentally friendly MXene synthesis. However, on comparison with fluoride-based methods, the use of this technique has some of the drawbacks like reduced yields, slower reactions, and less efficient elimination of the A layer.

3.3 Post-Treatment Strategies and Intercalation Chemistry

3.3.1 Delamination and Exfoliation

The stacked multilayer structures commonly formed after the synthesis process usually reduce the performance of the materials in various applications. In order to overcome from this issue, delamination of the MXenes are required to produce single or few-layer sheets. One widely used approach is to intercalate organic molecules or solvents such as tetrabutylammonium hydroxide (TBAOH), tetramethylammonium hydroxide (TMAOH), or dimethyl sulfoxide (DMSO) between the MXene layers [43]. Among the various solvents the commonly used one is the DMSO: MXene powder and DMSO are usually stirred for nearly 24 hours under an inert atmosphere, then washed and gently sonicated in water. This process enables interlayer delamination spacing from about 0.98 nm to over 2.5 nm, using mild sonication process [44]. Research indicates that parameters including temperature (25-80°C), DMSO concentration (50-100%), and immersion duration (6-48 hours) have a substantial impact on layer separation. When these conditions are optimized, the yield of monolayer MXenes can surpass 80% [45].

More recent approaches aim to improve the process energy efficient and environmentally sustainable. For example, using delamination agents like proteins and amino acids has been demonstrated to facilitate exfoliation with comparable efficiency but lower environmental impact. Other groups have also reported using a mixture of DMSO with water or alcohol to enable scalability. Furthermore, it has been proposed to use simple inorganic bases as delamination agents. In intercalation strategies, common materials used are urea, hydrazine, or DMSO that can intercalate between the MXene layers and align along the basal plane direction and increase the out of plane C-lattice parameter, which weakens the van der Waals interactions between MXene layers and enables their exfoliation [46].

3.3.2 Cation Intercalation and Property Tuning

Addition of various cations at different stages of synthesis enables fine tuning of material properties while retaining its original structure. Alkali metals such as K^+ , Na^+ , and Li^+ , alkaline earth metals such as Ca^{2+} and Mg^{2+} , transition metals like Ni^{2+} , Co^{2+} , Mn^{2+} , and organic cations like tetraalkylammonium and choline [47] are some of the examples of cations that can be introduced. Intercalation of MXenes often leads to efficient improvement in optical behavior, conductivity as well as electrochemical performance. For instance, intercalating $\text{Ti}_3\text{C}_2\text{T}_x$ films with alkali metals increases the conductivity to more than 11,000 S/cm, mainly through improved charge carrier transport and reduced interlayer resistance [48]. One of the works demonstrated that the

introduction of K^+ ions improved the electrical conductivity and surface structure, thus enhancing the performance of thick supercapacitor [49]. It was observed that the cations can be introduced to the MXenes either by themselves or by using an electric field. The process often involves the removal of water molecules from the interlayer and interaction with surface groups and is generally limited by a diffusion controlled [50]. Fine tuning of these methods has been the main focus of recent studies, including regulated techniques such as electrochemical interaction and the gradual change in the composition to modify the properties of MXenes.

3.4 Surface Termination Engineering

3.4.1 Fundamentals of Termination Chemistry

Surface terminations play a decisive role in the MXene characteristics because of their considerable atomic composition content of 25%. The formation of these surface terminations is associated with the preparation conditions and subsequent methods of the resulting plates. For example, in the case of MXenes based on carbonide, hydroxyl, oxygen, and fluorine atoms dominate in their content by varying the proportions, and the nature of these groups affects the properties of the material. In particular, oxygen terminations provide good adhesion and semiconductor properties, hydroxyl groups ensure high hydrophilicity and energy storage capability, and fluorine ensures chemical inertness but low electrical conductivity [51]. Research indicates that an appropriate balance of -OH and -O groups improves catalytic performance, particularly for reactions like hydrogen evolution [52]. Among the most common surface groups for Mxenes,

fluorine, hydroxyl, and oxygen are the most common, but recently, much attention has been paid to the synthesis of MXenes with other kinds of terminations, which opens up new opportunities for controlling their properties [53]. The analysis of the surface compositions of MXenes can be performed using time-of-flight secondary ion mass spectrometry (ToF-SIMS) and X-ray photoelectron spectroscopy (XPS). Figure 2 illustrates common MXene synthesis routes, serving as a basis for further investigation of terminations and providing additional approaches to tune MXene properties for different applications. All this makes MXenes attractive material for their further study and use.

3.4.2 Controlled Modification of Surface Groups

For the fine tuning of surface terminations by using the chemical and surface treatments researchers have proposed different approaches. The former one allows increasing the amount of hydroxyl groups via heating MXene suspension in an inert atmosphere around 200 - 400°C. which lead to the removal of fluorine. At the same time, the temperature above 500°C promotes dehydration of hydroxyl groups to form -O containing surface functional groups [54, 55]. Apart from this, the chemical etching of MXenes with alkali solution (NaOH or KOH) around between 60-150°C allows regulating the amount of surface groups. It was found that the treatment of MXenes with alkali solutions increases the contents of oxygen and hydroxyl groups and decreases the content of fluorine [56]. The ability to tune the surface chemistry of MXenes is a good opportunity to regulate their stability and electrochemical properties. Both the experimental and theoretical studies have established that the nature of surface groups affects the stability of MXenes.

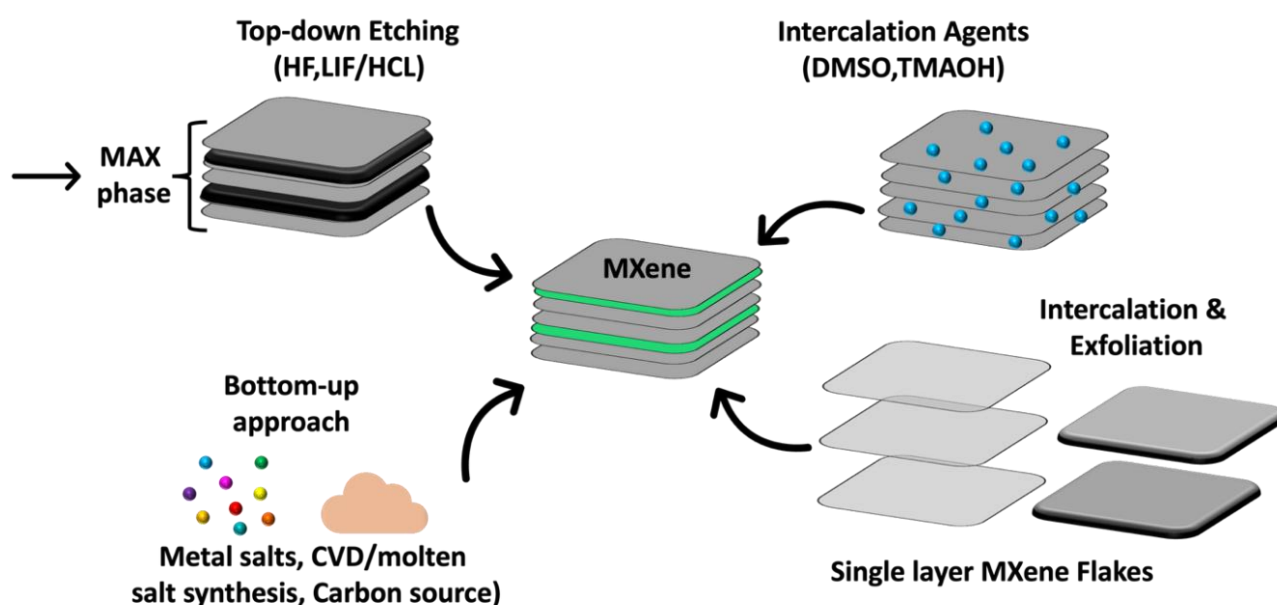


Figure 2. Standard processes for MXene preparation.

The possibility to control the surface terminations offers a good opportunity to improve the MXene properties. For example, the modification of MXene surface from hydrophilic to hydrophobic one is expected to improve its stability in various environments [57]. Moreover, it was found that changing the surface groups helps in changing the behavior of the material from metallic to semiconductor.

3.4.3 Emerging Surface Chemistries

Compared to the traditional terminations, MXenes can be synthesized with selenium, sulfur, nitrogen, and other halides as surface functional groups. MXenes with iodine, bromine, and chlorine termination are of particular interest due to their excellent control of chemical stability and conductivity [58]. Another promising direction is nitrogen terminated MXenes, where the functionalization can be achieved using hydrazine or ammonia plasma leading to -N, -NH₂, or -NH surface groups. These terminations are particularly interesting for sensor and biological applications. [59].

3.5 Advanced Characterization Techniques

3.5.1 Structural Characterization

For evaluating the structural characteristics of MXenes, X-ray diffraction (XRD) continues to be a core technique, providing key information on phase purity, crystallinity, degree of intercalation, and the interlayer spacing. One widely used sign of effective A-layer removal is the distinct shift of the (002) diffraction peak from about 9.2° in the original MAX phase to roughly 6-8° in the produced MXene, reflecting an expanded interlayer distance resulting from etching.

Depending on the various preparation methods, peak broadening can be assessed using the Scherrer equation which generally indicates crystallite sizes between 5 and 100 nm [60]. Recently progress in X-Ray based methods has made it possible to obtain accurate structural information. In particular, Zhang and his team developed a comprehensive approach, which combined conventional powder XRD with synchrotron measurements, allowing for high resolution structural characterization and detailed analysis of the layer attacking and interlayer interactions [61]. Moreover, statistical information on the effects of surface terminations on the crystal structure can also be analyzed using XRD methods, which gives an insight into the possible terminations induced structural changes. For the complete understanding of the analysis, HRTEM (high resolution transmission electron microscope) can be used to study the structure of the crystal at an atomic level. Similarly, aberration corrected STEM (scanning transmission electron microscope) can be utilized to study the layer arrangement, as well as defects and surface terminations. When combined with the XRD, STM (scanning tunnelling microscope) and

AFM (atomic force microscope), can be utilized to further analyze the MXene material in greater detail [62].

3.5.2 Surface Chemistry Analysis

XPS (X-ray photoelectron spectroscopy) is the most reliable analytical technique to study the surface chemistry of MXenes, being able to identify the surface termination, their percentage, and the oxidation states of the elements present. XPS is an essential method to characterize MXene oxidation state and evaluate its electrochemical performance by revealing the composition of contaminants on the surface of the material [63]. Diffraction-based methods are often less sensitive to changes in oxidation state, so the XPS method helps detect the onset of the oxidation process. High resolution scans of C 1s, O 1s, F1s and Ti 2p regions allow for determining the ratios of terminated groups on MXene surfaces and analyzing their electronic structure [64]. Advanced XPS techniques, such as environmental XPS, enable in situ detection of surface oxidation, and depth profiling XPS can be used to obtain information about lateral and vertical distributions of surface terminations. Several characterization studies have also shown that techniques such as FTIR, XRD, Raman spectroscopy, and UV-Vis can be used effectively to analyze the material and provide a comprehensive description of MXene properties. ToF-SIMS is another powerful surface analytical technique that enables lateral and depth analysis of MXene surface with high resolution and provides information about the distribution of different chemical species on the surface and inside the material [65].

3.5.3 Morphological and Physical Property Analysis

AFM provides a resolution sufficient to study MXene flake geometry on a nanometer scale. It is worth noting that experimental and computational studies have demonstrated the susceptibility of MXenes surfaces, for example, Ti₃C₂O₂, to hydrolysis. Furthermore, during surface reconstruction water molecules participate by chemically interacting with surface titanium atoms, breaking the Ti-C bonds to form Ti-OH bonds. This results in the release of hydronium ions into the solution, pointing out the importance of moisture in the degradation of MXenes [66]. The choice of strategies to prevent water attack, such as surface charging or conversion of surface oxygen to hydroxyl groups, is of great interest since they ensure the lowest possible interactions with water molecules and thus enhance the stability of the basal plane. AFM enables a detailed analysis of MXenes flake structure when combined with the SEM and TEM. Particularly, analysis of MXenes in a humidity-controlled environment using AFM results in a reversal swell upon hydration, providing valuable information about mechanical characteristics and interlayer water content. On the other hand, SEM and

FESEM allow us to estimate the surface structure of MXenes to analyze the morphology of individual particles, and examine the organization of thin films. Modern developments in environmental SEM open the possibility of directly observing MXene behavior under various conditions, including anoxic ones, making it possible to study oxidation processes and the mechanisms of MXene degradation [67]. Importantly, electromechanical vibration methods have proven effectiveness for rejuvenating partially oxidized MXenes, highlighting the need to better understand reversible degradation processes and the mechanisms behind their recovery.

4. MXenes in Sustainable Energy Technologies

4.1 Electrochemical Energy Storage

4.1.1 Lithium-Ion Batteries

MXenes, particularly $\text{Ti}_3\text{C}_2\text{T}_x$, have been considered as one of the promising electrode materials for in lithium-ion batteries (LIBs) because of their adjustable interlayer spacing, hydrophilic surfaces, and metallic conductivity. Unfortunately, their theoretical capacity is not always consistent with the experimental one. For instance, while the theoretical capacity of V_2CT_x is as high as 940 mAh g^{-1} , the experimental one is only 252 mAh g^{-1} [68, 69]. According to recent *insitu* XRD studies, the capacity of MXenes comes from two sources: intercalation of ions into the interlayer space and surface redox reactions [70]. During the lithiation process, the interlayer spacing is raised, which facilitates Li^+ ions into the interstitial sites without changing the structural arrangements. Another source of capacity in $\text{Ti}_3\text{C}_2\text{T}_x$ is the involvement of $\text{Ti}^{3+}/\text{Ti}^{4+}$ redox couples. The composition of $\text{Ti}_3\text{C}_2\text{T}_x$ and CoOHf can be charged and discharged at a high current density (2 A g^{-1}) for 1000 cycles, delivering a stable capacity of 802.4 mAh g^{-1} [71]. Restacked $\text{Ti}_3\text{C}_2\text{T}_x$ films possess excellent conductivity, yet their electrochemical performance was found to be insufficient at high charge/discharge rates. Electrochemical impedance spectroscopy revealed that the poor rate capability was caused by slow ion transport through the 2D channels of $\text{Ti}_3\text{C}_2\text{T}_x$ [72]. Quick insertion and extraction of protons can be achieved due to the increased space availability within the shear plane, while the other ions require more time for completing the process. One of the easiest ways to resolve this drawback is the introduction of carbon nanotubes (CNTs) as spacers. The resulting CNT@MXene composite demonstrated significantly higher capacity, rate capability, and stability than the $\text{Ti}_3\text{C}_2\text{T}_x$ film. Nevertheless, MXenes are prone to oxidation in organic electrolytes, which degrades their performance and structure [73].

A combination of TiO_2 and MXene enhances the conductivity through the formation of new electrical

pathways, reduces the activation energy of lithium ions and inhibits particles aggregation thus improving the discharge capacity and rate capability as compared to the original TiO_2 . The composite electrolyte membrane of a gel polymer containing PEO and LiTFSI coated onto the separator suppresses the polysulfide shuttle effect and enhances lithium sulfur cells with high storage capacities at varying sulfur loading and good cyclic stability after 200 cycles [74]. Fabricated flexible films with MXene, CNTs, and nickel coatings demonstrate high mechanical robustness and stable interlayer spacing with a higher capacitance value supporting portable supercapacitor applications with high energy and power densities [75].

4.1.2 Sodium-Ion Batteries

Sodium-ion batteries (SIBs) are considered as one of the inexpensive ways to store large amounts of energy, and MXenes are ideal for this type of battery due to their ability to allow for quick Na^+ intercalation. Theoretical studies demonstrate that $\text{Ti}_3\text{N}_2\text{O}_2$ would be more efficient than $\text{Ti}_3\text{C}_2\text{O}_2$ because of stronger bonds and a greater interlayer distance, which would allow more Na^+ ions to be accommodated within the sheets. This was proven experimentally as the Ti_3CNT_x showed improved cyclability over $\text{Ti}_3\text{C}_2\text{T}_x$, retaining higher capacities during long term cycles [76]. MXenes, on the other hand, suffer from oxidation, aggregation, and restacking, which decreases Na^+ conductivity as well as stability. Researchers have sought to modify the surface terminations and interlayer distances to allow for more Na^+ ion insertion [77]. Recently, the rate performance of MXenes has been improved by employing heterojunction architectures. In a recent study, a $\text{MoSe}_2/\text{MXene}$ composite prepared via a hydrothermal process followed by annealing formed a structure that mitigates volume variation and speeds up Na^+ ion transport by reducing the energy barrier for ion diffusion. Electrochemical measurements show that this material has exceptional capacity of (490 mAh g^{-1} at 1 A g^{-1}) and excellent cyclic stability, and is a promising candidate for future SIBs.

4.1.3 Zinc-Ion Batteries

Due to the abundance availability, safety, and appropriate redox potential for zinc material (-0.76 V vs. SHE) Aqueous zinc-ion batteries (ZIBs) have attracted attention for grid-scale energy storage [78, 79]. One of the proposed novel rechargeable Zn-MXene capacitor, which uses zinc nanosheets and Ti_3C_2 MXene as electrodes, demonstrates extraordinary durability and resistance to self-discharge. The prepared capacitor retains nearly 82.5% of its capacitance after 1000 cycles and is capable of total degradation within 7.25 days, outperforming other state of the art degradable supercapacitors and batteries. Noticeable self-discharge rate of the prepared device is only 6.4 mV h^{-1} , which was

superior to commercial systems, where usually, modified separators, electrolytes, or electrodes were required to solve this urgent problem. The self-discharge was dominated by a newly defined “static electricity-immune mechanism”, which could hamper the static electricity mediated adsorption process, providing an alternative strategy to tune capacitors with a long-standing self-discharge issue. To overcome the dendrite growth for aqueous Zn-ion batteries 2D nanomaterial coatings were introduced to engineer zinc anodes. To produce the protective film with homogeneous metal-ion transport during operation solution-based spray deposition technique was employed. Specifically, Zn anodes coated with MoS₂ support stable zinc nucleation to avoid dendrite growths and side reaction that interferes with electrostatic adsorption, offering a new strategy for mitigating the long-standing self-discharge issue in supercapacitors.

To address zinc dendrite growth a major obstacle for aqueous Zn-ion batteries 2D nanomaterial coatings have been applied to engineer zinc anodes. A solution-based spray process forms protective films that promote uniform Zn²⁺ transport during cycling. Specifically, Zn anodes coated with MoS₂ support stable zinc nucleation, reducing dendrite formation and minimizing side reactions. The MoS₂@Zn symmetric cells demonstrate cycling stability for more than 1000 hours 1 mA cm⁻² and exhibit enhanced performance under deeper cycling at higher currents. Moreover, fuel cells consisting of MnO₂ cathodes and the modified anode deliver a discharge capacity of 308 mAh g⁻¹ at 0.4 C and retain almost the same capacity over 100 cycles, demonstrating the potential of these 2D coatings in enhancing Zn-based batteries [79].

Recent studies show the further improvements in energy density and long-term stability of ZIBs [80]. V₂CT_x MXene is considered as a promising cathode material due to its layerlike structure, vanadium based redox reaction, and high conductivity. However, traditional etching methods using fluorinated etchant leads formation of F-termination, which results in sluggish transport and hydrophobic surface. An -OH rich V₂CT_x with K⁺ pillared interlayers (alk- V₂CT_x) was synthesized through a simple alkalization process, and resulted in the modification which endows it with enhanced ion transport and hydrophilic surface. As a cathode, alk- V₂CT_x delivers a high capacity of 498.2 mAh g⁻¹ at 0.1 A g⁻¹ and 195.1 mAh g⁻¹ at 30 A g⁻¹, with 96.2% capacity retention after 20,000 cycles. The flexible quasi-solid-state Zn battery that employs it as the cathode also maintains excellent performance under mechanical stress and at low temperatures, underscoring its promise for practical applications. This work demonstrates the importance of surface engineering on MXene-based cathodes [81].

Another way to address the drawbacks associated with Zn anodes, antimony (Sb) nanoarrays

were designed, where the Sb was used to form alloy of Zn-Sb that allows Zn storage while promoting uniform Zn deposition. The Sb nanoarrays fabricated on the freestanding Ti₃C₂T_x MXene films provide a 3D structure that enables dendrite free Zn plating/stripping. The MXene@Sb electrode delivers a capacity of 299.6 mAh g⁻¹ after 200 cycles at a current density of 50 mA g⁻¹ and retains 148.4 mAh g⁻¹ after 1000 cycles at 500 mA g⁻¹. This indicates the superior stability of the MXenes@Sb anode, which can be attributed to the Sb-MXene interface engineering that governs Zn behavior during cycling [82].

4.1.4 Potassium-Ion Batteries

Potassium-ion batteries (PIBs) are alternatives to Li-ion and Na-ion batteries because potassium is abundant and has a favorable redox potential (-2.92 V vs. SHE) comparable to that of Li. However, the larger ionic radius of K⁺ (1.38 Å) relative to Na⁺ and Li⁺ presents challenges. An anode material of Te-SnS₂/MXene composite was developed and demonstrated a much lower volume expansion (15.4%) than that of the SnS₂ anode (63.6%) after 5000 cycles, retaining a capacity of 165.8 mAh g⁻¹ at 10 A g⁻¹. The MXene electrode can self-adapt its interlayer spacing upon K⁺ intercalation, accommodating the larger ionic radius of K⁺ and causing much less damage to the electrode structure than graphite. However, intercalation of such a large ion may lead to limited diffusion because only stage-1 structure (interlayer spacing of approximately 20 Å) can host K⁺ ions. [83].

In the recent decades, potassium storage in carbon materials has been studied. One of the main advantages of potassium is that it can be stored not only through surface adsorption but also through intercalation between graphitic layers and leads to formation of graphite intercalation compounds (GICs). However, in the storage of carbon structures a multistage mechanism is involved with the formation of different compounds like KC₈₄, KC₈, etc., with specific voltage plateaus at various stages. Also, from the used lithium-ion batteries, graphite can be extracted and used in PIBs, supporting the sustainable development of battery recycling.

Also, another approach to store potassium in carbon structures is to use solvent co-interaction. Various combinations of electrode materials with different ions and solvents can be used to create a co-intercalated composition, where combination of ions and solvent molecules occupy interstitial space of a host lattice, forming three-dimensional porous lattice with an interlayer distance larger than 1 nm and the mechanisms of each ion batteries are depicted in Figure 3. This idea can be expanded to other types of materials and can be applied to batteries, supercapacitors, and catalysis [84].

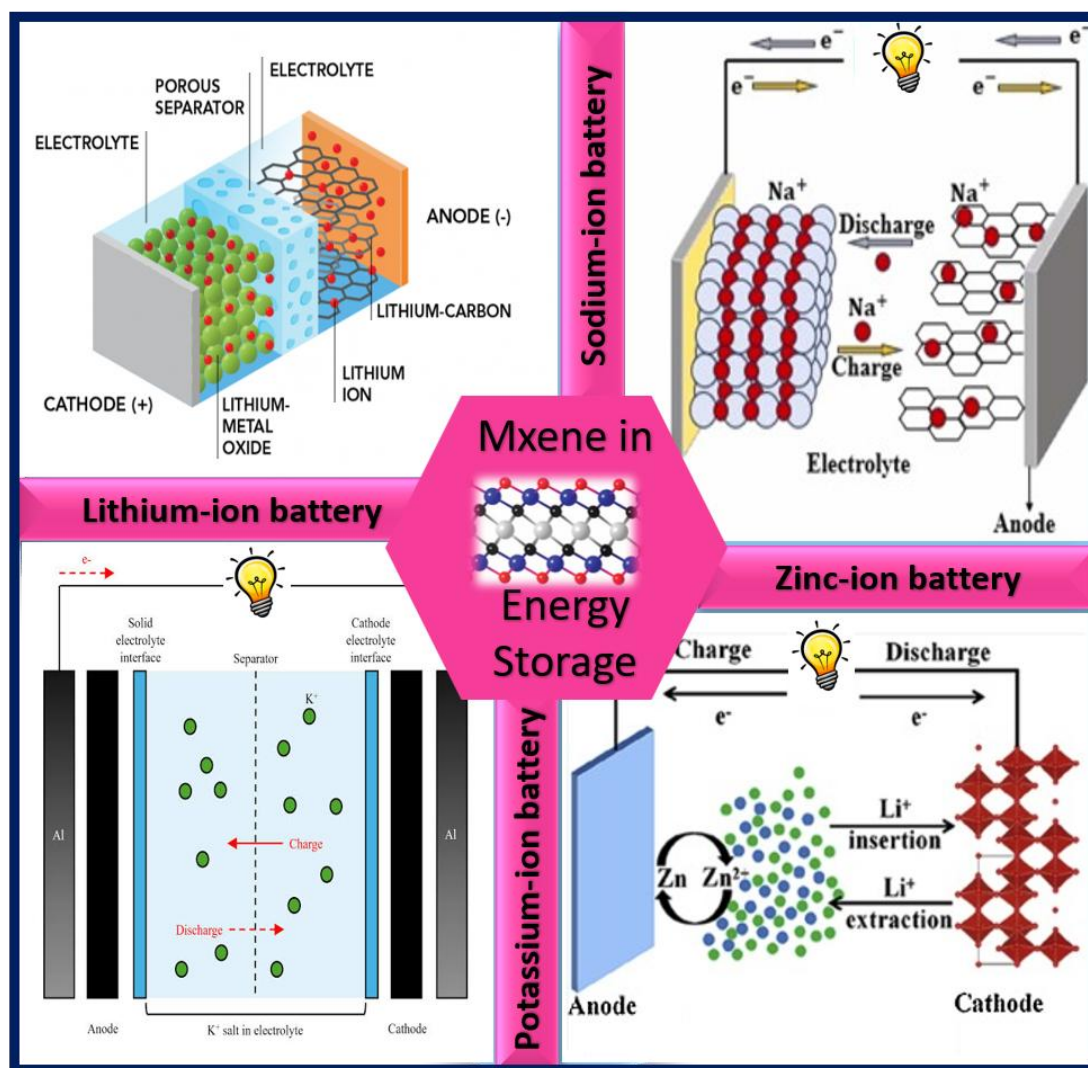


Figure 3. Mechanism of different ion batteries.

4.1.5 Pseudocapacitive Mechanisms and Benchmarking

MXenes are characterized with both the battery and supercapacitor-like properties due to their ability to exhibit pseudocapacitive behavior, associated with fast redox processes, which do not involve long-range ionic or electronic conduction [85, 86]. The pseudo capacitance of MXenes ($\text{Ti}_3\text{C}_2\text{T}_x$) was studied by electrochemical impedance spectroscopy (EIS) and a new equivalent circuit diagram was proposed, which accurately described the charge storage mechanism with a low error. It was found that the anodic oxidation of MXene started at approximately 0.3V due to water interaction, leading to the formation of titanium oxid with increased resistance, thus decreasing the charge storage [87]. The initial capacitance of 493 F g^{-1} decreases by 27.5% after 1000 cycles. The majority (around 85%) of the total capacitance is contributed by the surface-controlled processes, emphasizing the importance of the Mxene surface in the energy storage mechanism [88]. Besides the surface redox processes, the intercalation pseudo capacitance is another

important contributor to the capacitance of MXenes. Without the formation of a phase boundary MXenes layers can accommodate ions providing higher rate capability and also exhibit electrical double layer capacitance, owing to higher pore volume and surface area. For instance, $\text{Ti}_3\text{C}_2\text{T}_x$ with a surface area of $649.2 \text{ m}^2 \text{ g}^{-1}$ and a pore volume of $0.844 \text{ cm}^3 \text{ g}^{-1}$ showed a high specific capacitance of 633 F g^{-1} [89]. The enhanced electrochemical activity of MXenes arises from the formation of Ti-N and Ti-O bonds at defect sites, which also improves their energy storage performance. A flexible, freestanding N- $\text{Ti}_3\text{C}_2\text{T}_x$ electrode achieves a volumetric capacitance of 936.0 mF cm^{-3} at 1 V and retains 89.7% of its capacity at a high scan rate of 1 V s^{-1} . A corresponding high-energy supercapacitor delivers 104.9 Wh L^{-1} at 0.38 kW L^{-1} within a 2 V window, outperforming many devices in aqueous and organic media. This suggests that with suitable surface and structural engineering, MXene-based electrodes can serve as advanced materials for high-rate and high-density energy storage [90].

4.2 Supercapacitors and Hybrid Capacitors

4.2.1 Symmetric Supercapacitors

MXenes have emerged as promising materials for high-performance supercapacitors due to their metallic conductivity and pseudocapacitive charge storage behavior. A specific capacitance of 396 F g^{-1} was achieved at a current density of 1 A g^{-1} using ACP-5 M as a single electrode. When configured in a symmetric device, the ACP-5 M electrodes delivered a specific energy of 38.8 Wh/kg and a power density of 604 W/kg . Activated carbon derived from paddy straw has also shown good potential as an electrode material. It possesses a developed porous structure and excellent cycling performance, retaining 90.6% of its capacitance after 10000 cycles in 6M KOH [91]. Moreover, an increasing attention have been gathered for aqueous symmetric supercapacitors due to their environmentally friendly and high-rate capability, but the only difficulty is that the voltage is difficult to exceed 1.2 V, limiting their energy density. $\text{Mo}_{1.33}\text{CTz}$ -based SSCs delivered a higher operating voltage of 1.4V in a concentrated 19.5M LiCl electrolyte and achieved a peak energy density of more than 38.2 mWh cm^{-3} at a power density of 196.6 mW cm^{-3} .

The most researched MXene is $\text{Ti}_3\text{C}_2\text{T}_z$, showed excellent performance in LiCl electrolyte as well, with an energy density of 41.3 mWh cm^{-3} at 165.2 mW cm^{-3} with a higher voltage of 1.8 V. However, it was found that $\text{Ti}_3\text{C}_2\text{T}_z$ demonstrated a steeper decrease in the energy density at higher power outputs than the MO-based

MXenes [105]. The detailed electrochemical properties of different MXene based SSCs are depicted in Table 1.

4.2.2 Asymmetric and Hybrid Configurations

In order to overcome the voltage limitations of symmetric supercapacitors MXene based Asymmetric supercapacitors (ASSCs) has been explored. One of the MXene with excellent conductivity and layered structure is $\text{Ti}_3\text{C}_2\text{T}_x$, but its efficiency is hindered by the restacking of nanosheets. To solve this problem, yolk shell structured $\text{NiCo}_2\text{S}_4@\text{Co}_3\text{S}_4$ nanocages were anchored to the $\text{Ti}_3\text{C}_2\text{T}_x$ which resulted in an increase in the active sites and reduced the agglomeration of sheets. As a result, the specific capacitance achieved was 1872 F g^{-1} at 2 mV s^{-1} with 92.2% retention after 12000 cycles. The low capacitance that is exhibited by the pristine MXene supercapacitors is primarily attributed to the stacking of sheets, but to overcome this problem and enhance the performance NiCo_2S_4 can be used. In a similar study, a hybrid device was created using MXene/ NiCo_2S_4 and rGO electrodes that delivered an energy density of 38.7 Wh kg^{-1} and a power density of 6137 W kg^{-1} [106]. Another study of anchoring NiMoS_4 nanoparticles on Ti_3C_2 MXenes using a hydrothermal method and this has resulted in enhancing the number of active electrochemical sites while minimizing capacity loss that is incurred during the oscillation of volumes resulting in an ASSC with power density of 40.5 Wh kg^{-1} and energy density of 810 W kg^{-1} .

Table 1. Electrochemical performance of various MXene-based solid-state supercapacitors.

Electrode Material	CR (CR%/Cycle)	SC (F g^{-1})	ED (Wh kg^{-1})	PD (W kg^{-1})	Ref.
MXene $(\text{Ti}_{0.5}\text{V}_{0.5})_3\text{C}_2\text{T}_x$	69/100000	387	5.6	5210.3	[92]
MXene/N-doped	83/5000	71	12.78	1080	[93]
MXene $\text{Ti}_3\text{C}_2\text{T}_x/\text{Te}$	90/3000	150.6	67.8	151	[94]
MXene $\text{Ti}_3\text{C}_2\text{T}_x/\text{Se}$	90/3000	96	30	124.7	[95]
MXene $\text{Ti}_3\text{C}_2/\text{MoSe}_2$	93/5000	350	48	500	[96, 97]
MXene $\text{Ti}_3\text{C}_2\text{T}_x/\text{MoS}_2$	91/10000	439	6.3	30000	[97]
MXene $\text{Ti}_3\text{C}_2\text{T}_x/\text{MoS}_2$	72.3/10000	303.8	5.1	298	[98]
MXene V_2CT_x	January 88, 5000	551	48.6	552	[99]
MXene $\text{Ti}_3\text{C}_2\text{T}_x/\text{V}_2\text{O}_5$	April 70, 5000	319.1	18.43	603.2	[100]
MXene $\text{Ti}_3\text{C}_2\text{T}_x/\text{PANI}$	April 71, 4000	272.5	31.18	1079.3	[101]
MXene $\text{Ti}_3\text{C}_2/\text{PANI}$	April 70, 5000	536	26.9	933.9	[102]
MXene/ PANI/MoO_x nanowires	91.5/10000	450	19.53	1610.11	[103]
MXene/rGO	-/10000	88.9	24.2	1400.6	[104]

Table 2. Electrical properties of MXene-based ASSCs.

Electrode Material	CR (CR%/Cycle)	SC (F g ⁻¹)	ED (Wh kg ⁻¹)	PD (W kg ⁻¹)	Ref.
MXene Ti ₃ C ₂ T _x /NiCo ₂ S ₄ @Co ₃ S ₄	92.2/12000	1533	241.9	1125	[109]
MXene/NiCo ₂ S ₄	–	1211	38.7	6137	[106]
MXene Ti ₃ C ₂ /NiMoS ₄	89/9000	1288	40.5	810	[107]
MXene Ti ₃ C ₂ /NiCo ₂ O ₄ Nanowire	91.5/10000	253	90	2880	[108]
MXene- NiCo ₂ O ₄ @NiCo-MOF/CC	90/6000	2091	56.7	750	[110]
MXene/NiO	90/5000	73.3	10.7	3333	[111]
MXene Ti ₃ C ₂ T _x /NiAl	92/4000	1276.83	37.86	1056.55	[112]
MXene/NiAl	78/3000	1600	27.6	255	[113]
MXene/NiAl/NiAlP	91/8000	2589.3	81.1	1800	[114]
MXene V ₂ CT _x /NiV	80.95/10000	1658.19	54.19	750	[115]
MXene-PPy/rGO	8.8/10000	408.2	11.3	500	[116]
MXene/CNTs/Ni ₃ S ₂ /Co ₉ S ₈	88.57/10000	1827.5	78.4	699.3	[117]
MXene Ti ₃ C ₂ T _x /VS ₂ /Fe ₃ O ₄ @rGO	90.7/10000	228.4	73.9	728.2	[118]
MXene/Graphdiyne nanotube	88.2/10000	337.4	19.7	750	[119]

In another study, a hybrid system was created by growing NiCo₂O₄ nanowires on Ti₃C₂ MXene [106,107]. The use of Ni foam that acted as a conductive support enhanced the ion transport and the structure. As a result, the ASSC delivered a capacitance of 253 F g⁻¹ and 91.5% retention after 10,000 cycles [108]. Table 2 shows the performance of various MXene based asymmetric capacitor configurations.

4.2.3 Flexible and Wearable Applications

The need of wearable electronic devices, such as foldable smart phones, health monitors, and smart watches, require a development in novel flexible, and light weight energy storage systems. MXene based materials are considered as promising candidates for such applications due to their excellent conductivity, abundance of electrochemically active sites, high surface area, and tunable pore structure [109]. MXene nanosheets can be combined with one-dimensional and two-dimensional materials, such as graphene, carbon nanotubes (CNTs), carbon nanofibers, and polymers, to suppress interlayer restacking and expand interlayer spacing [106]. This strategy has led to the development of a flexible sandwich-like MXene/CNTs@Ni film, where CNTs@Ni helps stabilize the MXene layers. The resultant binder-free, self-supported electrode demonstrated a remarkable capacitance of 990.8 F cm⁻³, 1.4 times that of pure MXene and 2.4 times that of MXene/CNTs electrodes. Flexible symmetric supercapacitors based on these films exhibited high

energy density (14.5 Wh kg⁻¹), power density (2571.4 W kg⁻¹), and cycling stability [107].

One study introduced a carbon dot intercalation method using calcium alginate (CA) gel carbonized within MXene layers. This produced dense MXene/CA films with an expanded interlayer space, thereby improving ion diffusion and increasing the accessible active surface area. The composite displayed remarkable specific capacitance (372.6 F g⁻¹ or 1244.6 F cm⁻³ at 1 A g⁻¹) while retaining 93.5% capacitance after 30000 cycles. The all solid state supercapacitor (ASSC) achieved using this composite showed a bulk energy density of 27.2 Wh L⁻¹ and a peak power density of 13.1 kW L⁻¹ [108, 110]. Another study improved Ti₃C₂T_x MXene performance by optimizing electrode structure and surface chemistry and creating flexible, binder-free P-MXene/CPAQ-A electrodes. The fabricated electrodes showed exceptional electrochemical performance with a capacitance value of 532.9 F g⁻¹ at 5 mV s⁻¹ and 97.1% retention at 20 A g⁻¹ after 40,000 cycles, while maintaining almost 100% coulombic efficiency [110]. In addition to the energy storage field, MXene based devices hold great potential in pressure sensing applications. For instance, a reduced graphene oxide (rGO) based pressure sensor was engineered using a hierarchical attached structure on a polydimethylsiloxane (PDMS) substrate. The resulting sensor displayed high (133.003 kPa⁻¹ for <40 kPa), a broad detection range (0-300 kPa), rapid response time of (<27 ms), and good mechanical durability over 10,000 cycles [111, 112].

Researchers engineered a self-healing MXene-based pressure sensor by introducing hydrophilic groups and aramid nanofibers (ANF) to strengthen interlayer bonding. The obtained sensor exhibited a high sensitivity (208.7 kPa^{-1}), tensile strength (65.5 MPa), toughness (210.9 MJ m^{-3}), and maintained 98% of the initial sensitivity after the first self-healing and 80% of the sensitivity after six cycles [112]. Researchers also constructed 3D porous MXene/AuNP composites using freeze-drying and self-reduction methods, these materials provided a hydrophilic microenvironment with an open structure, allowing for stable enzyme retention and enabling potential applications in biosensors [113]. The formation of $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_3\text{AlC}_2$ composites significantly enhances gas sensing performance. These composites demonstrated an extraordinary sensitivity and selectivity to NH_3 with low detection limit of 50ppb and good stability within 120 days. This optimized composite structure can overcome the shortcomings of high detection threshold and insufficient stability of the existing MXene based sensors [114]. Generally speaking, these research works fully demonstrated the importance of MXene for constructing multifunctional and robust flexible electronic devices.

4.3 Electrocatalysis for H_2 , O_2 , and CO_2 Conversion

4.3.1 Hydrogen Evolution Reaction (HER)

Hydrogen evolution is one of the most promising reactions in clean energy technologies. Precious metals, such as ruthenium and platinum, are highly efficient catalysts for this reaction, while there are some limitations due to the low abundance and cost. However, to overcome these limitations scientists have shifted to build a cost-effective catalyst from by utilizing more abundant materials like the transition metals. Metal phosphides, nitrides, carbides, oxides, sulfide, and even carbon nanostructures have shown great potential as electrocatalysts for HER [120]. Nevertheless, most of them exhibit low electrical conductivity and poor electrochemical stability in aqueous media. MXenes are two dimensional transition metal nitrides, carbides, or carbonitrides, and these promising materials are found in various applications from catalysts to energy storage. MXenes possess high inherent electrical conductivity, a layered structure with a large specific surface area, and excellent electrochemical stability. Interest in MXenes was triggered by the discovery of titanium carbide $\text{Ti}_3\text{C}_2\text{T}_x$ MXene by the group of Gogotsi's in 2011 [116]. Since that time, roughly thirty MXenes have been synthesized experimentally, while more than one hundred have been predicted theoretically. Among these promising candidates are high-entropy MXenes containing four different transition metals, such as TiVNbMoC_3 and TiVCrMoC_3 [117].

MXenes are typically described by the formula $\text{M}_{n+1}\text{X}_n\text{T}_x$, in which M denotes a transition metal (such as

Ti, Nb, or V), X refers to carbon or nitrogen, and T_x indicates surface terminations like -F, -OH, or -Se. They are synthesized from MAX phases ($\text{M}_{n+1}\text{AX}_n$), which include group 13-14 elements like Al or Si in the A-site. Etching agents such as hydrofluoric acid or a combination of LiF and HCl are used to selectively remove the A layer while preserving M-X bonds. The resulting layered MXenes are further exfoliated using organic solvents, such as DMSO. These few-layered sheets typically have thicknesses under 1 nm and lateral sizes in the millimetre range [121].

4.3.2 Oxygen Reduction Reaction (ORR)

MXenes are also being explored for oxygen reduction reactions (ORR), especially in alkaline media. Carbon materials with defects, especially when combined with MXenes, have shown promising results. One example is a porous, nitrogen-rich carbon/MXene composite developed using polypyrrole as the nitrogen source. This material achieved nitrogen doping levels up to 9.6 wt% and incorporated Ti_3C_2 MXene into its carbon matrix. The nitrogen-doped pores acted as the active sites for ORR, although the role of MXene in enhancing conductivity was not clearly explained [119]. However, MXenes face stability issues in alkaline solutions. Studies by Wang and colleagues showed that $\text{Ti}_3\text{C}_2\text{T}_x$ loses conductivity and undergoes oxidation within one to two weeks when stored in aqueous media [122]. Their further work revealed that hydroxyl ions accelerate MXene degradation in basic conditions, such as KOH, as evidenced by rapid pH drops and increased Ti (IV) content in XPS analysis [123]. These findings help in evaluating the long-term oxidative durability of MXene-based under alkaline conditions for ORR catalysts.

MXenes have yet to be explored in combination with single atom non-precious metal catalysts. Zhou and Sun reported Cu single atom anchored to Ti_3C_2 for efficient ORR catalysis [124], while Tian and Yang employed ZIF-8, a zinc-based metal-organic framework doped with iron and hybridized with $\text{Ti}_3\text{C}_2\text{T}_x$ to yield Fe-N-C catalysts [125]. Given the relatively large size of ZIF-8 crystals (20 to 500 nm), their integration with multilayer MXenes is challenging and hence monolayer MXenes were utilized. The interesting thing during the synthesis procedure is the inhibition of MXene decomposition by isolating the high temperature carbonization step of Fe-N-C (1100°C) from the secondary treatment at 350°C involving $\text{Ti}_3\text{C}_2\text{T}_x$. The resulting catalysts which is more active than Pt/C exhibits increased durability with no degradation upon 10000 cycles. Ti_4N_3 MXene treated with TBAOH displayed high -OH surface coverage, which enhanced HER activity after passivation layer removal. This treatment lowered the overpotential by almost 300mV at -10 mA/cm^2 . Differences in the delamination agents used did not meaningfully affect performance, while ORR onset and half-wave potentials were comparable among OH-terminated Ti_4N_3 samples.

These findings highlight the versatility of surface engineering of nitride based MXenes for catalytic applications [52].

4.4 Photothermal and Photovoltaic Applications

4.4.1 Photothermal Conversion and Solar Steam Generation

Solar-driven desalination is becoming a promising approach to address the emerging worldwide water crisis, but they suffer from high cost, limited durability, complicated fabrications, and low energy conversion efficiency. Recent studies shows that interfacial evaporators with photothermal materials have high solar absorbance, low thermal conductivity, and excellent mechanical stability which has attracted extensive attention. A 3D evaporator composed of aramid nanofiber (ANF) aerogel with MXene coating (MX@ANF) was designed and demonstrated to possess superb evaporation performance and coating with this gel enhanced the solar absorption and photothermal conversion ability. The hydrophilic property of MXene renders continuous water transportation through the capillary force inside the MX@ANF aerogel. Under 1 sun irradiation (1 kW m^{-2}), the 3D evaporator achieved a high evaporation rate of $1.48 \text{ kg m}^{-2} \text{ h}^{-1}$ and a solar to steam conversion efficiency of 93.8% for solar desalination [126]. A multifunctional solar interfacial evaporator (SIE) based on MXene/Fe-MOF@cellulose acetate/polyvinylpyrrolidone composite (MXM@CP) aerogel was fabricated via electrospinning combined with suction filtration. The hybrid MXM@CP aerogel demonstrated excellent photothermal conversion performance with the evaporation rate reaches $1.1 \text{ kg m}^{-2} \text{ h}^{-1}$ under 1 sun irradiation. The SIE shows outstanding VOCs removal performance with a degradation efficiency of 82.8% for benzene in water, which exhibits great potential for simultaneous solar evaporation and VOCs degradation [127].

For the first time a novel composite material was developed using the recycled rock wool (RW) waste, which is then transformed into a solar evaporator containing MXene, zeolitic imidazolate framework (ZIF-67), and reduced graphene oxide (rGO), forming a hybrid structure called ZMG. This hybrid design led to better, increased water transport, and wettability greater light absorption through the internal microchannels. A 3.5 cm tall evaporator can achieve an evaporation rate of $3.81 \text{ kg m}^{-2} \text{ h}^{-1}$ and a solar conversion efficiency of 153.7% per sun due to additional energy harvested through sidewall evaporation. Additionally, it maintains a stable rate of $3.55 \text{ kg m}^{-2} \text{ h}^{-1}$ for 12 hours in a 20 wt% NaCl solution without salt accumulation. They can reject 99.8% of salt ions and remove dyes, oils, and other pollutants in an outdoor environment to yield a low-cost, durable water purification technology [128]. Moreover, they have developed metamaterial MXenes (m-MXenes)

with alternating MXene and organic layers to improve the photothermal conversion performance. The m-MXene lower the refractive index and promote internal light reflection to increase the absorption and reach the conversion efficiency of 90%. The m-MXenes, when coated on liquid crystal elastomer (LCE) fibers, create light responsive actuators that can lift weights close to 6900 times their mass and deliver a work density six times greater than that of human muscles. These fibers may be used to make artificial muscles, grippers, and bistable mechanical devices [129].

4.4.2 Photovoltaic Applications and Perovskite Solar Cell Integration

The growing need for scalable and efficient photovoltaic technologies has driven the exploration of MXenes as attractive materials with high electronic conductivity ($\sim 10^4$ - 10^5 S/cm), with tunable bandgap (0.7-2.0 eV), and excellent optical transparency (>90%). Compared to conventional transparent conducting materials, such as ITO or TiO_2 , MXenes demonstrate superior charge-carrier mobility, mechanical flexibility, and a broad range of work functions (4.0-5.5 eV). This has promoted their consideration as transparent conductive electrodes, electron and hole transport layers, and even light absorbing components in modern solar cells. Recent research on MXenes conductivity and electrostatic properties highlights the effect of various synthesis approaches, including HF etching, molten salt treatment, or fluoride free methods. The performance of MXene based solar cells is determined by their unique combination of optoelectronic characteristics, processability and stability, which are comparable to other 2D materials, including graphene, TMDs, or black phosphorous. Particular attention is paid to the potential of MXenes in perovskite, organic, silicon, and tandem solar cells, where their contribution to power conversion efficiency (PCE), charge mobility, and overall stability is under intense investigation. Surface engineering, passivation approaches, and the employment of AI-driven materials design are playing an important role in overcoming oxidation and the defects related to interface. Moreover, hybrid structures based on MXenes and perovskites, TMDs are also being explored to improve charge transport, leading to enhanced stability [130].

Whereas in another work, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanoflakes were used as a low-temperature ETL in planar perovskite solar cells (PSCs). UV-ozone treatment of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene increased the Ti-O bonds on the surface of the MXene, which enhanced electron transport and inhibited charge recombination. As a result, devices treated for 30 min achieved a peak power conversion efficiency (PCE) of 17.17% [131]. Oxygen plasma treatment $\text{Ti}_3\text{C}_2\text{T}_x$ MXene resulted in the formation of Ti-C bonds from Ti-O bonds. The process modulated the work function and reduced defects,

therefore, a PCE of 18.9% was achieved with good stability, retaining 80% of the initial PCE after 750 hrs of storage and significantly outperforming the comparative device without plasma treatment [132]. Another research group reports on the record breaking PCE of 22.77% for devices, where $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes were used as an ETL achieving 95% of stability retention even after 1000 hrs of testing under highly humid conditions (40-60% RH). Since their first appearance in 2018, MXenes were utilized in different configurations for PSCs, namely, as additives to perovskite precursors solution for absorbent layer fabrication, as transport layer, electrodes, and interfacial layers. Being added to the perovskite precursor solution, MXenes participate in the regulation of the crystallization process, promoting layer grain formation, passivating surface defects, and providing hydrophobicity, which reduces the degradation rate: additionally, MXenes work function can be easily tuned to match the charge transfer needs of the device. On the other hand, the ETL of PSCs based on MXenes enables a better alignment of the energy levels and facilitates charge extraction [133].

4.4.3 Photodetector Applications and Optoelectronic Devices

MXenes have also shown great potential in photodetectors. For example, Guo *et al.* demonstrated a UV photodetector based on crossed Zn_2GeO_4 nanowire (NW) networks and $\text{Ti}_3\text{C}_2\text{T}_x$ MXene with enhanced charge transfer enabled by the heterojunction (p-n junctions) between Zn_2GeO_4 and MXene [134]. By optimizing the MXene content (0.03 wt%), the device exhibited a high responsivity of 20.43 mA W^{-1} , which was significantly higher than that of the photodetector based on only Zn_2GeO_4 NWs. In another work, CsPbBr_3 nanocrystals were blended with $\text{Ti}_3\text{C}_2\text{T}_x$ MXene to fabricate a photosensitive composite film. The charge transfer mechanisms in the composite were demonstrated: however, the fabricated photodetectors exhibited limited performance in terms of on/off ratios and response times, probably due to the high content of conductive MXene. Similar observations were reported for the photodetector based on MXene quantum dots [135].

Ahn *et al.* reported two dimensional titanium carbide MXene sheets as a transparent conductive electrode, providing high conductivity ($11,670 \text{ S/cm}$) and a work function of 5.1 eV. To passivate the surface against oxidation with enhanced stability, conductive polymers has been used. Po Lu *et al.* proposed the $\text{ZnO-Ti}_3\text{C}_2$ MXene ETL for perovskite nanocrystal LEDs, while Yi *et al.* developed MXene-GaN van der Waals heterostructures for high-speed, self-powered LEDs and photodetectors [136]. Overall, MXenes appear to make a substantial contribution to the field of optoelectronics. Although stability and synthesis are still challenges the

adjustable bandgap of these materials and their ability to be used in quantum dots open up new possibilities, for photodetectors, LEDs and other advanced technologies. With worldwide demand projected to hit \$121.5 million by 2027, efforts should be focused on addressing current limitations and support in industrial deployment [137].

4.5. Comparative Analysis of MXenes with Other 2D Materials

MXenes are often compared to such materials as graphene, carbon nitride, and MoS_2 , each of which has its own advantages and disadvantages. MXenes are two-dimensional transition metal carbides, nitrides, or carbonitrides with excellent electrical and electrochemical properties. They have a metal like conductivity due to the presence of layered structures and also ensures a good electron exchange and free movement of electrons, with high concentration of ions in the interlayer space. The hydrophilic nature of MXenes contributes to their interaction with an electrolyte, which enhances their capacitance [138, 139]. For example, MXenes demonstrated a capacitance in supercapacitors, which could reach 1872 F g^{-1} in a composite material [140]. They also showed excellent results in terms of cycling stability and battery capacity. Hybrid composites based on MXenes and graphene or carbon nanotubes demonstrate their advantages, combining the high electrical conductivity of graphene or carbon nanotubes and the high surface energy of MXenes. Compared to graphene, MXenes show better storage characteristics. Whereas, the only drawback of graphene is that they cannot store ions inspite of its excellent mechanical strength and electrical conductivity. Carbon nitride, in turn, is mainly used in photocatalysis, which is limited by the low conductivity of this material. Although MoS_2 has good electrochemical properties, MXenes demonstrate better ion transport characteristics with increased capacitance [141, 142].

MXenes are considered as one of the excellent materials for water purification technologies due to their high conductivity and electrochemical activity, absorbing a significant number of various pollutants such as heavy metals, organic ones, and salts. Graphene base materials, despite offering a large surface area and mechanical robustness, are hydrophobic, which limits application in the purification of water unless they are modified to become hydrophilic [143]. Carbon nitrides, in turn have lower conductivity and mechanical robustness, but offer excellent photocatalytic activity, allowing for pollutants removal. MoS and other similar materials also offer good photocatalytic properties but may be a challenge to produce at large scale and may degrade over time [144, 145]. The comparison between MXenes and other two materials is presented in Table 3.

Table 3. Comparison of MXene-Based Photocatalysts with Other 2D Materials

Material / System	Pollutant Type	Degradation Efficiency (%)	Reaction Time	Light Source	Recyclability & Stability	Key References
MXene-based composites ($\text{Ti}_3\text{C}_2\text{T}_x/\text{TiO}_2$, MXene/g- C_3N_4 , MXene/MOFs)	Methylene Blue (MB), Rhodamine B (RhB), Congo Red, Tetracycline, Ciprofloxacin	9-99%	20-90 min	Visible / Simulated solar (Xe lamp 300-500 W)	Stable for 3-5 cycles; slight oxidation after repeated use	[155]
g- C_3N_4 and doped/heterostructured g- C_3N_4 (Fe/ g- C_3N_4 , g- $\text{C}_3\text{N}_4/\text{TiO}_2$)	Dyes, antibiotics, phenolics	90-99%	30-120 min	Visible light (LED / solar simulator)	Recyclable up to 5 cycles with minor loss	[156]
Graphene / reduced graphene oxide (rGO) composites (rGO/ZnO, rGO/ TiO_2 , rGO/ MoS_2)	RhB, MB, Tetracycline, Phenol	95-99%	15-40 min	Visible / UV-Vis	Excellent structural stability; >90% efficiency retained after 5 cycles	[157]
MoS_2 -based 2D photocatalysts (MoS_2 /g- C_3N_4 , $\text{MoS}_2/\text{TiO}_2$, expanded MoS_2)	MB, RhB, Tetracycline	90-98%	20-60 min	Visible (LED / solar)	Stable for 4-6 cycles; minor aggregation observed	[158]
Black Phosphorus (BP) / BP-based heterojunctions (BP/ TiO_2 , BP/g- C_3N_4)	MB, RhB, Phenolic compounds	80-95%	20-60 min	Visible / Simulated solar	Poor stability in air/water; oxidation limits recyclability	[159]

MXenes have efficient charge separation and transfer in photocatalysis and provide multiple active sites for improving photocatalytic activity. Carbon nitride was reported as one of the visible light responsive catalysts. Meanwhile, when MXenes were combined with carbon nitride, Schottky junctions were constructed, [146] which promotes charge separation and reduces recombination in photocatalytic hydrogen evolution. One of the excellent conductivity materials is graphene with an ideal support in photocatalysis for enhancing the charge transfer and stability [147]. MoS_2 is an efficient co-catalyst for generating hydrogen through photocatalysis due to promoting electron transfer and accelerating the efficiency of semiconductor photocatalysis. When combined with TiO_2 , CdSe and CdS it enhances the photocatalytic efficiency under visible light radiation [148].

5. MXenes in Environmental Remediation

Due to the growing concerns over pollution from industrial discharge, agricultural runoff, and municipal waste requires new combination of materials which can be versatile and effective in the removal of various contaminants from the environment. MXenes have demonstrated extraordinary performance in water

purification, removing more than 95% of heavy metals, and appear to be promising multifunctional materials for addressing multiple environmental problems. This section discusses the possibilities for using MXenes and their composites for environmental applications and provides an overview of the mechanisms that underpin their ability to remove various pollutants [149].

5.1 Water Treatment

5.1.1 Heavy Metal Adsorption

Water contamination by toxic heavy metals such as cadmium, mercury, arsenic, and chromium is a serious environmental problem because even trace levels endanger human health. MXenes have been proven to remove these ions from water via surface complexation by hydroxyl and oxygen groups, ion exchange, electrostatic interactions, and redox route [150]. Due to their layer structure and high surface area, MXenes have a high affinity for absorbing various metals and anions. Pb^{2+} removal from water using MXene prepared by in situ HF etching was studied by examining pH, contact time, adsorbent dose, and temperature to identify optimal removal conditions. The adsorption process fit better to the Langmuir isotherm model, indicating that adsorption occurred in monolayer state

[151], and the process was found to be spontaneous and entropy driven. The adsorption capacity over multiple cycles remains highly stable at 90%, demonstrating its effective reusability. Nonetheless, the issue Pb^{2+} adsorbent recycling and A layer waste management after etching process still needs to be addressed.

MXene's has a surface charge that comes from groups such as $-\text{O}$, $-\text{OH}$, and $-\text{F}$ that are formed during etching. The surface charge of MXene lets MXene absorb both cations and anions and the capacity of MXene to do so depends on the water pH and the targeted species. Electrostatic interactions of MXene are a factor, for binding pollutants that carry opposite charges, especially inorganic ions and radioactive elements. An innovative membrane that combines silver nanoparticles and multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene embedded in a porous polyethyleneimine cryogel showed more than 99% mercury removal within 24 hrs [152]. Thus, the hybrid material with a high surface area and active sites can exhibit excellent adsorption capacities (up to 1280 mg/g), rapid kinetics, and resistance to interference from other water constituents, which might be promising for mercury removal.

5.1.2 Degradation of Organic Pollutants

Persistent organic pollutants, such as residues from pharmaceutical, dyes, and pesticides pose another major risk to water safety as these chemicals can remain

in water for a long time and cannot be broken down easily. As shown in figure 4, MXene-based photocatalysts have garnered attention for such applications due to their ability to facilitate advanced oxidation reactions [153]. The incorporation of MXenes with other materials has enabled efficient electron transfer, improved visible-light absorption, and enhanced ROS (reactive oxygen species) generation. For example, the FeS/MXene nanocomposite lowered the bandgap of FeS and prolonged charge carrier lifetimes by forming a Schottky junction. This promoted the formation of active species like $\cdot\text{OH}$ and $\cdot\text{O}_2^-$ radicals, which drove the degradation of tetracycline under visible light [153]. A separate study demonstrated that the DA-M100 heterojunction, consisting of MIL-88A (Fe) and MXene, accomplished a degradation rate exceeding 90% for sulfamethoxazole and removed over 95% of heavy metals such as Cr (VI) within one hour [154].

Its effectiveness was linked to efficient separation of photogenerated electron-hole pairs and strong photo-Fenton reactivity. $\text{Ti}_3\text{C}_2\text{T}_x$ based MXenes have also been combined with porphyrin nanofibers, forming composites that removed over 97% of Rhodamine B under sunlight. These materials displayed improved charge transfer and photocatalytic efficiency due to synergistic interactions between MXene and the porphyrin matrix.

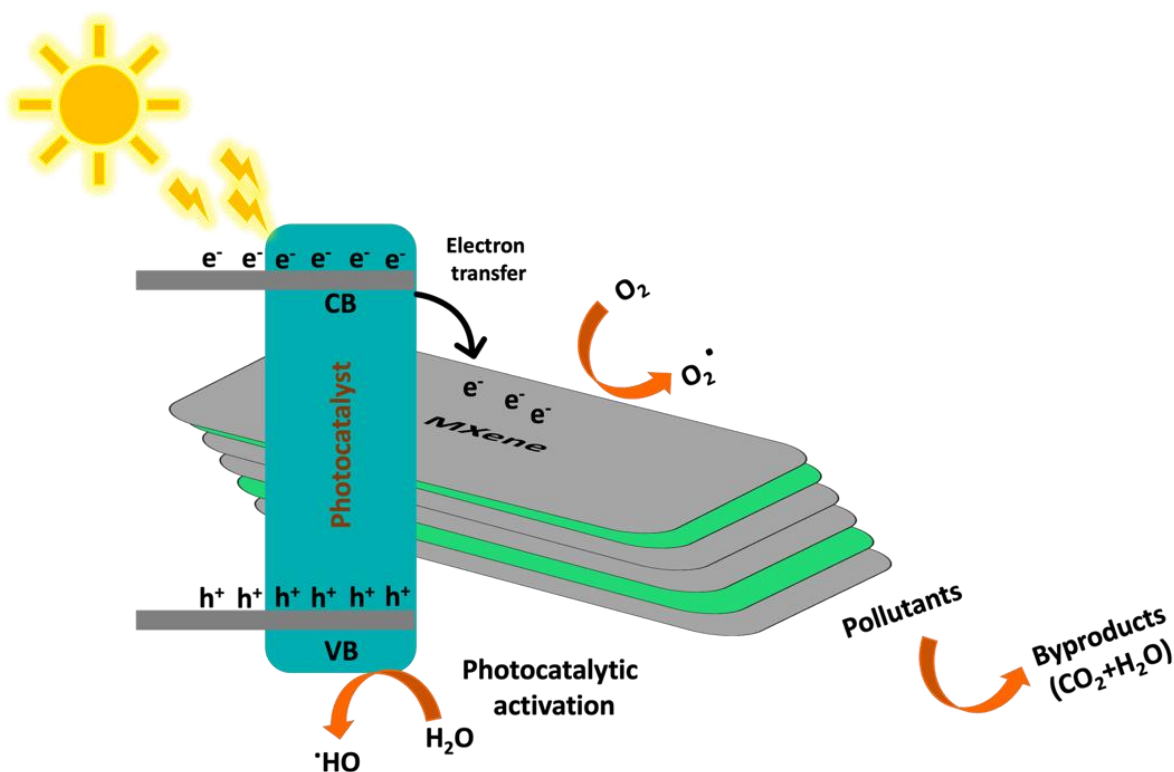


Figure 4. Charge transfer mechanism of the Mxene photocatalyst under visible light exposure.

Microwave-assisted degradation of dyes, such as methylene blue, further illustrates MXene's catalytic capabilities. In just 10 minutes, a 2D $\text{Ti}_3\text{C}_2\text{T}_x$ catalyst achieved nearly complete degradation with minimal catalyst loss over multiple cycles. Optimization by response surface methodology confirmed the best operational conditions for maximum efficiency. A ternary $\text{Fe}_2\text{O}_3\text{-SiO}_2\text{/MXene}$ nanocomposite removed 98% of tetracycline under visible light, thanks to enhanced light absorption and efficient charge separation in the FeS/MXene matrix [153]. Similarly, $\text{MoS}_2\text{/MXene}$ heterostructures demonstrated strong PDS activation and complete pollutant degradation within 50 minutes, even in the presence of competing ions [160].

5.1.3 Desalination and Capacitive Deionization (CDI)

With the depletion of freshwater resources, capacitive deionization is gaining more attention as an energy efficient desalination technology. Due to the excellent electrical conductivity and tunable surface properties of MXenes, they are widely used in CDI electrodes. For instance, the SAC (salt adsorption capacity) of the prepared porous $\text{Ti}_3\text{C}_2\text{T}_x$ MXene electrodes achieved 118 mg/cm^3 at 1.2 V in 10,000 mg/L NaCl solution [161]. Increasing the spacing between the layers by treatment in NaOH increased the interlayer spacing from 9.8 to 12.2 Å and improved the sodium storage capacity. Hybrid structures of MXene with polymer, metal, or carbon are potential candidates for developing next generation CDI electrodes. For example, 3D MXene aerogels, which possess a network of pores with 10-50 μm width, enabled higher ion accessibility and achieved higher SACs up to 200 mg g^{-1} with minimal capacity retention after repetitive testing. In another work, report on a symmetric all MXene CDI cell with high electro-adsorption efficiency. The prototype withstood regeneration cycles and maintained performance. MXene interlayer spacing, surface area, and functional group density can be tuned by adjusting etching and post-etching conditions. Delamination can further increase surface area and enhance charge storage. [162].

5.2 Air Purification and Gas Sensing

MXenes, as a new class of two-dimensional materials, exhibit many excellent properties like high surface area, chemical and thermal stability, hydrophilicity, and eco-friendliness. All these advantages show greater performance than traditional ceramic materials for the development of multifunctional materials in gas storage and air purification. MXene composites have been demonstrated to be able to capture various harmful gases and particulate matter with high efficiency at ambient conditions. This leads to reduced energy consumption in the process of pollution control and storage. They are promising candidates for storing light gases such as CO_2 , CH_4 , and H_2 . Many

studies have focused on the adsorption mechanism of MXenes for a gas storage including chemisorption, electrostatic interaction, and van der Waals forces. Another important application of MXenes is related to CO_2 capture from flue gas after combustion or directly from ambient air [163].

5.2.1 Ammonia and Nitrogen Dioxide Sensing

The detection of ammonia (NH_3) at room temperature is of great significance for clinical diagnosis and environmental monitoring. However, MOS (metal oxide semiconductor) gas sensors often face a challenge due to the need of high-power consumption and limited sensitivity. Herein, a hydrothermally synthesized NiO@MXene composite sensor was reported, which not only retained the excellent catalytic property of NiO but also combined with the conductivity and surface atomic structure of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. The heterostructured morphology of NiO@MXene was verified by a series of characterization. The NiO@MXene sensor exhibited an enhanced gas sensing performance to 100 ppm NH_3 with a sensitivity value of 5.7-fold higher than that of the pristine NiO. Besides, the NiO@MXene sensor possessed outstanding sensing capability to trace level NH_3 gas (100ppb) and excellent stability (keeping 97% of the initial value after 60 days). More importantly, this sensor showed satisfactory humidity tolerance (47.54% response at 80% RH). The improved sensing performance was attributed to the MXene/NiO heterostructure with enhanced carrier transportation capacity, UV response ability, and gas adsorption/desorption capacity. The NiO@MXene sensor demonstrated great potential in clinical diagnosis and breath [164]. $\text{Ti}_3\text{C}_2\text{T}_x\text{/CuO}$ nanocomposites were designed and fabricated by a facile, eco-friendly hydrothermal approach. The as-prepared samples were characterized by XRD, SEM, TEM, and BET analysis. Mesoporous structure was created with the introduction of CuO nanoparticles into the $\text{Ti}_3\text{C}_2\text{T}_x$ matrix, with an increased surface area than that of the pristine material. Moreover, CuO nanoparticles endowed more oxygen vacancies and participated in the formation of lattice oxygen during the sensing process. Benefiting from the synergistic effect of $\text{Ti}_3\text{C}_2\text{T}_x$ and CuO, the response of the $\text{Ti}_3\text{C}_2\text{T}_x\text{/CuO}$ sensor to 50 ppm NO_2 at room temperature reached 56.99%, which was about five times higher than that of the $\text{Ti}_3\text{C}_2\text{T}_x$ sensor. In addition, this sensor also exhibited a rapid response and recovery speed (16.6s and 31.3s), good selectivity and reproducibility, as well as excellent stability (keeping 90% of its initial value for 40 days). This work provided a feasible strategy for heterostructured MXene-based nanocomposite, which can be applied to the commercialization of NO_2 detection with high performance [165].

MXene based sensors with SnO₂ nanoparticles decoration were developed by a hydrothermal approach. MXene/SnO₂ heterostructures showed extraordinary sensitivity and selectivity to ammonia at concentrations from 0.5 to 100 ppm under room temperature. The superior sensing performance was mainly attributed to two factors: one was that MXene acted as a conductive matrix and selective layer toward ammonia, and another was that the fermi level difference between MXene and SnO₂ induced interfacial charge transfer, which increased the electron density of SnO₂ and enhanced the sensing performance. A wireless sensor based on an LC antenna circuit and a MXene/SnO₂ heterojunction prepared by low temperature confirmed ceramic (LTCC) technology was demonstrated, which exhibited a remarkable fast response time (<30s) and consistent measurement results, suggesting the great potential of MXene/SnO₂ heterostructures for practical gas sensing applications [166].

5.2.2 Volatile Organic Compound Removal

In the recent decade industries have developed rapidly, which lead to the release of harmful substances, such as hydrocarbons, heavy metals, volatile organic compounds, and microbes, into water resources, moreover, the conventional treatment methods do not have an efficient control over removing the pollutants. Among the various options, adsorption is proved to be efficient and environment friendly, and using selective adsorbents that can capture trace pollutants is one of the promising approaches. MXenes, benefiting from their electrical conductivity, hydrophilicity, surface functionalization, and high stability, have become an emerging family of materials in water purification, and the effects of surface modification on MXene nanoparticles to improve their adsorption capacity and selectivity were investigated. Besides, their cost effectiveness and potential environmental impact were evaluated to confirm the feasibility of large-scale implementation in industrial wastewaters treatment. Furthermore, the problems of toxicity and synthesis barriers were identified and solutions were proposed [167].

MXenes were also found to be efficient in the capture of toxic gases, including SO_x, NO_x, NH₃, H₂S, and CH₄. An activation energy for CO₂ uptake was reported to be as high as 3.69 eV with a loading capacity of 8.25 mol/kg. MXenes can be used in fixed-bed and flow-through systems to remove toxic gases and to adsorb or photo catalytically degrade organic pollutants, including dyes, pharmaceuticals, and soil contaminants. For instance, 97% methylene blue decomposition was achieved by MXene-assisted Fenton reaction. A high percentage of pharmaceuticals was removed by in-situ reduction, for instance, ranitidine (91.1%) while other compounds were removed at 81.8-84.8%, respectively. Increased removal rate of the material was due to the

active surface sites, semiconductor MXene nature, and interfacial interactions. Similar results were demonstrated for the removal of heavy metals and radionuclides. MXenes also exhibit antimicrobial activity and are safe to aquatic organisms, for instance, green microalgae [168]. While studies on the combination of MXenes and TMDs are limited, initial studies demonstrate high potential. In particular, a Ti₃C₂T_x/WSe₂ hybrid sensor showed ultra-high response, low noise, and quick response for the detection of volatile organic compounds (VOCs). The hybrid sensor exhibited an increase in ethanol sensitivity (>12 times) compared to the pristine Ti₃C₂T_x. Due to the limited edge interactions with water molecules, moisture effects are reduced enabling selective, sensitive, rapid VOC detection in portable field devices. [169].

5.3 Soil Remediation and Antimicrobial Activity

One of the serious problems in food security and agricultural is the pollution of soils by heavy metals, pesticides, organic pollutants, and pathogens. MXenes exhibit a high surface area and a variety of surface chemistry that can be tuned to remove a broad spectrum of pollutants, including heavy metals, pharmaceuticals, dyes, and agrochemicals. Various studies have demonstrated their capacity for adsorbing different types of contaminants through surface engineering, acid or base treatment, and intercalation strategies to enhance their affinity for certain pollutants. For example, Ti₃C₂T_x MXenes functionalized with amine and thiol groups were used for simultaneous enrichment of heavy metals in soil and food by ultrasonic assisted dispersive micro solid-phase extraction (d-μ-SPE) method. Trace amounts of Cd²⁺ and Pb²⁺ were quantified with limit of detections (LODs) of 0.12 and 2.30 ng/mL for Cd²⁺ and Pb²⁺, respectively, with high extraction recovery (> 97%) and good batch repeatability. The bifunctional MXenes showed great potential as sensitive and efficient adsorbents for the simultaneous determination of Cd²⁺ and Pb²⁺ ions in soil and food samples [170].

A new type of hybrid microfiltration membrane was developed from titanium carbide-based MXene (Ti₃C₂T_x) deposited on the surface of dry mycelium by electrochemical deposition, which demonstrated exceptional performance in removing lead from contaminated water. The fabricated MyMX membranes showed excellent Pb (II) removal efficiency (87-99%) and rapid sorption capabilities even at high metal ion concentrations. Fourier transform infrared spectroscopy and X-ray photoelectron spectroscopy revealed that the predominant mechanisms responsible for Pb (II) removal from the solution were electrostatic interactions and complexation with mycelial proteins and MXene's functional groups. The membranes exhibited outstanding water permeability and higher efficiency compared to many other membranes made from

polymers or MXene for heavy metal removal purposes [171].

Another soil study found that adding MXenes with biochar and nanoscale zero-valent iron (nZVI) improves lead immobilization in calcareous soils. Different amendment levels changed lead speciation, which increased binding to organic matter and carbonate phases. The authors have observed a significant decrease of bioavailable Pb in the treatment with 5% of biochar, as estimated by the DTPA and EDTA extraction methods. Moreover, the application of MXenes and biochar amendments resulted in a better maize growth due to the detoxication of the soil and the improvement of its nutrient status and contents. The MXenes increased the ion exchange capacity of the soil, whereas biochar provided the carbon matrix for the metal sequestration [172]. MXenes can be used for their excellent antimicrobial properties, which inhibit gram positive and gram negative bacteria by disrupting cell membranes. MXenes also show antifungal and antiviral activity against diverse microorganisms, including both the enveloped and non-enveloped viruses. Their application is proposed for the preparation of wound dressings, medical devices coatings, smart textile materials, and food packaging, where antimicrobial properties are required. The photothermal and photodynamic antimicrobial approaches are also discussed, which utilize the properties of MXenes to target various pathogens and even cancer cells with light irradiation. The antimicrobial properties of MXenes are promising, though their biocompatibility and toxicity should be evaluated in detail [173].

Niobium-based MXenes such as Nb_2CT_x and $\text{Nb}_4\text{C}_3\text{T}_x$ were found to be antibacterial due to their ability to penetrate the cell membrane, forming pores and disrupting the integrity of internal structures. Observation of the cell membrane leakage and rupture confirmed the bactericidal properties in MXenes. In addition, MXenes could induce the production of reactive oxygen species (ROS), including the single oxygen atom, hydroxyl radicals, and hydrogen peroxide, leading to cell membrane oxidation and intracellular damage owing to ROS-mediated protein, lipid, and DNA damage. MXenes' negative charge enhances the binding to bacterial surfaces, which boosts ROS-driven killing. $\text{Nb}_4\text{C}_3\text{T}_x$ shows higher oxidative potential compared to Nb_2CT_x due to the wider interlayer spacing and improved electron transfer. Environmental safety is increasingly important because of exposure risks; for instance, Ti_3C_2 MXene degradation has been studied under horseradish peroxidase (HRP) and peroxide conditions. The reaction resulted in pore formation in the MXene layers and the generation of titanium dioxide nanoparticles with CO_2 release. The process significantly reduced the cytotoxicity of MXenes, but *Daphnia magna* still exhibited considerable bioaccumulation (137.36 $\mu\text{g}/\text{mg}$ of dry tissue) of titanium [174].

With the presence of soil colloids $\text{Ti}_3\text{C}_2\text{T}_x$ stability and degradation behavior in groundwater has been reported. The soil components like sodium humate and montmorillonite, enhances the degradation efficiency of MXene through the interaction of carboxyl and hydroxyl groups, whereas the natural soil with few reactive sites showed a less prominent effect. This implies that environmental factors have great influence on the behavior of MXenes, which transformation in soil and water should be carefully taken into account. With the exacerbation of ecological pollution caused by industrialization, the materials like MXenes can provide a promising way for ecological restoration, which can effectively remove organic and inorganic pollutants. In addition, the antibacterial and photocatalytic properties also endow the potential application in different fields, while several key problems including surface chemistry, scalable synthesis strategy, and environmental interactions should be addressed [175].

5.4 Integrated Remediation Systems and Process Intensification

The development of integrated MXene-based systems is a promising strategy towards the effective treatment of multiple pollutant types through synergistic treatments such as adsorption, photocatalysis, and membrane separation, among others. This technique has been proven more efficient than the conventional individual methods [176]. Hybrid processes have proven effective, as well as energy-intensive and reduces secondary waste production. Due to the failure of conventional wastewater treatments plants, microplastics has become a major challenge in water pollution. Forward osmosis (FO) a tertiary treatment has become one of the sustainable alternatives to existing processes like ultrafiltration, nanofiltration, and microfiltration. FO has proven to be energy-efficient and has high selectivity, and recent research has focused on developing Fouling-resistant membranes with improved performance. Recent study created a new composite membrane by embedding hybrid nanoparticles consisting of metal-organic frameworks (MOFs) and sulfobetaine zwitterions within the active layer of TFC membranes. ZW/MOF (UiO-66-NH_2) NPs were prepared using post-synthetic free radical copolymerization. This led to the formation of uniform polymer shells around the MOF nanocrystals and improved surface wettability by 73% and increased the negative surface charge.

Introduction of ZW/MOF nanomaterials into FO membranes increased the performance of water flux by 28% and reduced reverse salt flux. In addition, antifouling experiments with organic pollutants and MPs showed that the membranes were fouled less significantly, only by 17%, while the control membrane was fouled by a substantial 60%. Moreover, the modified membrane was able to recover by 90%, showing that

fouling was reversible, while the recovery for the unmodified membrane was only 70%. In this way, the authors emphasize that MOF-based hybrid nanomaterials can be used for enhanced FO membranes for emerging pollutants such as MPs [177]. On the other hand, MXenes are also investigated for their roles as components of protective coatings for various applications. In this regard, MXenes, uniformly distributed in various polymer matrices, can impart specific functions to the resulting coating, such as barrier, conductive, or mechanical ones. A review of MXene-based composite coatings and their fabrication techniques, with a focus on applications in flame resistance, antibacterial surface design, electromagnetic interference shielding, multifunctional platforms combining sensing with water-repellency, and photothermal conversion [178]. Finally, MXenes and their hybrid analogues are one of the promising materials for integrated environmental technologies for the simultaneous removal of several pollutants from soil, air, or water. However, their application requires further studies to ensure cost-effective and scalable fabrication and long-term stability and investigation of their impact on the environment [179].

6. MXene-Based Composites & Hybrid Architectures

Nanosheet structure of MXenes tend to exhibit poor air stability, low restacking, and insufficient mechanical properties. These issues can be resolved by developing hybrid and composite materials with MXenes. Nanosheet structures provide additional qualities of other materials along with unique MXene properties. Particularly, hybrid structures based on MXenes demonstrate high electrical conductivity and hydrophilic character on the surface, alongside good mechanical flexibility and stability. These materials are

considered for a variety of applications, from EM shielding, flexible electronics, and systems requiring liquid flow [180]. The property of shielding against electromagnetic interference (EMI) is primarily connected to the high level of conductivity and special architecture of MXene films, so when EM waves hit the surface of such material, the impedance mismatch leads to reflected waves. However, the waves that penetrate the surface are subject to attenuation through the MXene film. First, eddy currents are induced by the periodic potential along the layers of the material, thus dissipating a part of their energy. Moreover, the [presence of titanium and surface groups in MXene ($\text{Ti}_3\text{C}_2\text{T}_x$) contribute to the formation of local dipoles, which also dissipate the electromagnetic energy. Therefore, the described mechanisms are responsible for the significant shielding of EM waves by MXene films

Nevertheless, the significant of up to 4 g/cm^3 makes them less desirable for aerospace applications and other areas in which weight plays a critical role. To overcome this, scientists have integrated the porous structures into dense MXene films. The pores reduce the overall weight while simultaneously increasing the surface area of the electromagnetic wave interaction, hence enhancing the energy attenuation [181]. Figure 5 shows a Schematic illustration of the electromagnetic waves transfer across the MXene.

6.1 Polymer-MXene Films for Flexible Electronics and EMI Shielding

Different strategies have been proposed for the fabrication of MXene/polymer composites with high flexibility and low density for applications in wearable electronics and electromagnetic interference (EMI) shielding.

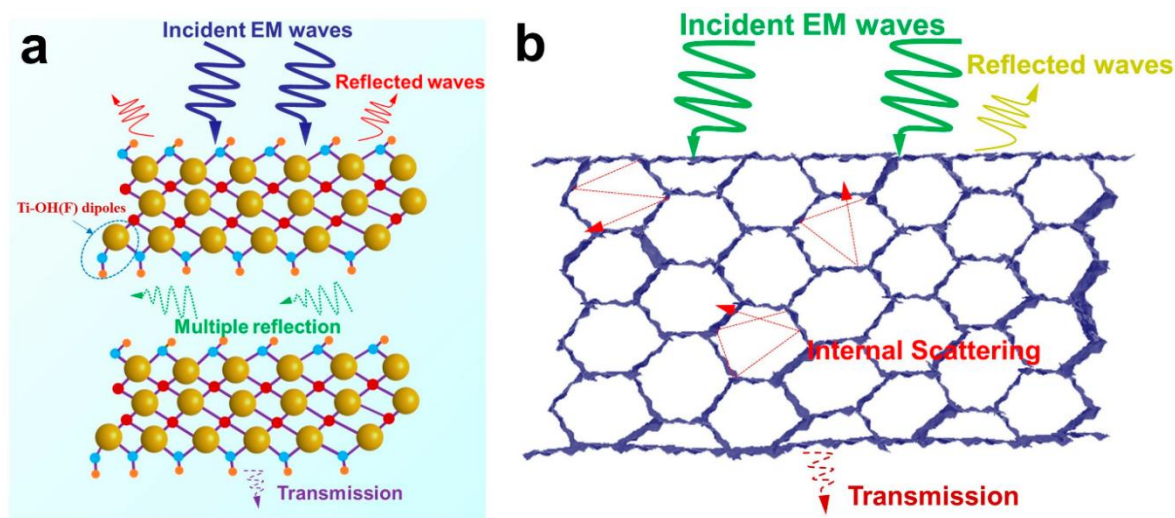


Figure 5. Schematic depiction of electromagnetic wave transmission through (a) an MXene film and (b) a 3D porous MXene film [181].

MXenes can be well dispersed in a variety of common solvents by virtue of their hydrophilic surface terminations and can be formed into films with a variety of solution processing approaches, including solution casting or layer-by-layer assembly [182].

6.1.1 Flexible Electrode Applications

MXene/polymer composites have made significant contributions to modern flexible electrodes design. Their combination of metallic conductivity with mechanical stretchability has allowed their successful application in sensors and conductive films. The authors proposed a simple approach using EGaIn liquid metal as an exfoliating agent and binder for MXene and expanded graphite fillers in a polyacrylic acid matrix. The composite demonstrated outstanding thermal conductivity (1.88 W/m·K) and electromagnetic interference (EMI) shielding effectiveness (52 dB) [183]. Another design used a hierarchical graphene/MXene foam for simultaneous electromagnetic shielding and thermal conductivity [177]. Built on a highly porous, conductive graphene oxide/MXene core-shell scaffold, the prototype delivered excellent thermal conductivity, energy storage, and cooling for high-power electronics. The foam was experimentally validated as a good candidate for prolonged operation of modern high-performance electronics because it could effectively dissipate heat from active areas after long-term chip operation and this property was found to significantly increase the lifespan of such devices. A similar approach was taken when preparing PANI/ $\text{Ti}_3\text{C}_2\text{T}_x$ MXene composite films using polyaniline (PANI) cationic conductive polymer [184]. The authors demonstrated that the 3D network of MXene nanosheets and PANI increased interlayer spacing and improved ion transport properties. Covalent bonds between MXene and PANI were found to enhance the composite's mechanical properties, and for the sodium-ion batteries the prototype demonstrated promising results.

6.1.2 Electromagnetic Interference Shielding Performance

MXene-based films, which contain nitrogen substituted for carbon in their crystal lattice, exhibit enhanced conductivity and provide ultra-wideband electromagnetic interference (EMI) shielding effectiveness. $\text{Ti}_x\text{C}_y\text{N}_{x-y-1}\text{T}_z$ MXenes with the enhanced content of nitrogen demonstrated the highest conductivity (up to 35000 S/cm) and shielding effectiveness at a wide range of frequencies. The study established the link between the content of nitrogen and EMI shielding effectiveness: MXenes with enhanced content of nitrogen are promising materials for EMI shielding applications due to their high conductivity. A safe wearable heater design was described, fabricated using flame-retardant aramid fabric and MXene; to ensure strong adhesion to the fibers, the fabric was

plasma-treated. The resulting textile-type heater was lightweight and flexible, demonstrated rapid heating, a high EMI shielding effectiveness (35.7 dB), and excellent flame retardancy. The carbonized MXene provided additional flame retardancy by acting as a heat-resistant barrier, which can be used for wearable electronic devices. [185]. MXenes need further investigation; only a few representatives of this class of materials were tested. There is a need for developing new methods for MXene synthesis that are compatible with sustainable development concepts, and for exploring more materials of this type. Due to their hydrophilicity, MXenes can only be used in aqueous media, which limits the design of MXene-based composites. Therefore, attention should be paid to the development of hydrophobic MXenes [186]. High electron conductivity and a layered structure allow MXenes to demonstrate excellent EMI shielding effectiveness. Electromagnetic waves are reflected from the free electrons in the MXene layer. The reflected component of waves is accompanied by absorption due to eddy currents that appear in the MXene layers and subsequent scattering of electromagnetic waves inside the material [187]. Further research is needed to optimize the design of MXene-based EMI shields and to identify their potential application in next-generation EMI shielding devices. Although the results of recent studies are promising, the challenges posed by the properties of MXenes should be addressed. Three-dimensional MXene-polymer structures were proposed as effective EMI shields with reduced thickness, which is advantageous. Such design allows the additional possibility of introducing a variety of functions [188].

6.1.3 Multifunctional Integration and Smart Materials

The modern MXene-based composites can simultaneously provide electro-magnetic interference (EMI) shielding, thermal and sensory functions. One paper reported the design of a poly (vinylidene fluoride) (PVDF)-based composite incorporating both cobalt and MXene by using CO_2 assisted foaming process. The partial oxidation of MXene into TiO_2 in the composite contributes interfacial polarization to the overall EMI shielding mechanism. As a result, the composite can achieve an EMI shielding effectiveness of up to 45.6 dB with a thermal conductivity as high as 1.28-1.36 W/m·K and an impedance matching of 67.1%, suggesting the excellent performance of the composite. As mentioned above, the wearable electronics require the ability of self-healing to restore their original performance. A self-powered heater which was composed of polycaprolactone (PCL) fibers surface-modified with MXene and embedded with AgNWs was demonstrated in another work. Interestingly, by introducing MXene, the pristine PCL matrix (with a low melting point of 60-61 °C) could be healed at 60-61 °C without any external stimulus. The healed wire demonstrated a recovery of electrical resistance to the level of the original one, even if the wire was completely cut through. This design can

find applications in long-term stable flexible devices [189]. Another study reported a stimuli-responsive MXene/polyvinyl alcohol film with shape-programmable property. The MXene layer not only reinforced the hydrogen bonding of PVA matrix, but also participated in the cross-linking system as a node. The film demonstrated a unique response to the water stimulus and could memorize the target shape without any additional stimulus after certain period. Such property is beyond the ability of traditional shape-memory polymers and can be applied in soft robots or stimuli-responsive controlled drug release [190].

6.2 Metal/Oxide Heterostructures and Single-Atom Catalysts

With the combination of metallic or metal oxide nanostructures, hybrid MXene interfaces were created that demonstrated unprecedented optical, catalytic, and electronic properties. This hybrid network used MXene's excellent conductivity and abundance of active sites, while the additional components provided new opportunities for fine tuning of the properties. Hydrogen is regarded as an energy carrier with high energy density and zero carbon emissions; therefore, its efficient production is of great interest to the scientific community. This review article focuses on recent studies of MXene-based heterostructures in catalytic hydrogen evolution, with an emphasis on synthesis approaches, interfacial design strategies, and hybrid design principles that improve activity. A comparison was made between different heterostructures in terms of electronic structure modifications and catalytic performance enhancement. Finally, the remaining challenges and opportunities in this area were discussed, including long-term stability, scalability, and environmental impact [191].

SACs on MXene substrates have unique properties for the hydrogen evolution reaction (HER). Due to the MXenes excellent conductivity and stable structure, its surface can be easily adjusted to provide more termination sites (-O, -OH, -F), which can be used as an anchoring site for isolated metal atoms with enhanced charge transfer. This unique SAC can fully utilize noble metals for green hydrogen production through water cleavage, and it is of great significance to reduce the consumption of platinum and explore new materials. By regulating the preparation process of MXene, materials with different morphologies can be prepared, such as delamination and crumpled structure, so as to adjust the surface area. This section mainly introduces and discusses some important morphology factors related to HER and reviews several typical preparation methods [191]. Kong *et al.* prepared $\text{Ti}_3\text{C}_2\text{O}_2$ QDs/Graphene heterostructures and studied their HER mechanism. It was found that hydrogen atoms were preferentially adsorbed on the titanium sites. The interaction between the graphene support and C-O terminated $\text{Ti}_3\text{C}_2\text{O}_2$ QDs caused the d-band center to

shift by 0.4-0.5 eV relative to the isolated $\text{Ti}_3\text{C}_2\text{O}_2$ QDs, bringing the adsorption free energy close to the optimal range. Ren *et al.* prepared $\text{MoS}_2@\text{Mo}_2\text{CO}_2$ hybrid catalysts and found that H atoms preferably adsorbed on the oxygen sites. The charge transfer between the MoS_2 and Mo_2CO_2 components led to the metallization of the interface, and the contribution of the two parts to the hydrogen adsorption energy can be combined to modulate the Gibbs free energy change. In the case of the N doped MXene supporting Ru SAC, Ti-N, N-Ti-O bonds were formed. The pyrrolic N coordinating Ru can anchor the ruthenium atoms by electron transfer, and the number of state densities near the Fermi level increases, thus enhancing the HER performance. Co single-atom anchored engineering on V_2CT_x also achieved electron transfer through the orbital of O, which facilitates the reaction of water dissociation, and the intermediate d band center of the system increases the desorption performance of the intermediate, thus enhancing the reaction performance [192, 193].

In one study, the authors demonstrated that a mixture of isolated Pt single atoms with small Pt nanoclusters anchored on MXene can be an efficient catalyst for HER. The as-prepared $\text{Pt}_1+\text{Pt}_n/\text{MXene}$ catalyst by an impregnation method showed a low overpotential of 61.3 mV and a small Tafel slope of 32.5 mV per decade at 10 mA/cm² in acidic media. Combined with XAFS and DFT analysis, the improved performance was rationalized by the synergistic effects between single Pt atoms and Pt nanoclusters on MXene, which enhances hydrogen adsorption capacity. This study provided a strategy for designing multifunctional noble metal catalysts by introducing multiple active sites [194]. Apart from the zero and two dimensional heterostructures, other designs have also been proposed to tune interfacial electronic properties. In a study, $\text{Ti}_3\text{C}_2\text{O}_2$ quantum dots (QDs) were grown on graphene with a slight lattice distortion, inducing favorable electronic structures for HER with a calculated ΔG_{H} of -0.21 eV. The combination of different dimensional materials offers unprecedented design space for creating MXene-based HER catalysts. The strategies can be extended to construct MXene QDs/ gC_3N_4 or MXene QDs/phosphines heterostructures. Hydrogen is regarded as a high-density and zero-emission energy carrier. By integrating electrocatalysts, with MXene-based SACs, into HER, hydrogen production can be achieved economically and efficiently. Although Pt is the most efficient electrocatalyst for hydrogen evolution, its application is limited by the high cost. To address this drawback, exploring alternative electrocatalysts such as transition metal sulfides or carbides, or by increasing the active site availability by reducing particle sizes to single atoms or small clusters. MXene provides an ideal support with unique layered structure and good carrier mobility for constructing SACs. Moreover, the electronic properties of MXene can be regulated by engineering surface

termination to tune hydrogen adsorption free energy and enhance HER activity [195,196].

6.2.2 Metal Oxide Heterostructures

The combination of MXenes with metal oxides yields MXene/metal oxide hybrid materials that simultaneously exhibit high conductivity and semiconductor properties, e.g., tunable band structure and efficient charge transfer. Through the formation of a new interface, hybrid materials enhances the photocatalytic and electrochemical properties of MXene with enhanced charge transfer capability. For instance, the integration of Ti_2N and $\text{Ti}_3\text{C}_2\text{T}_x$ leads to a $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_2\text{N}$ interface that is beneficial for the fabrication of ammonium ion aqueous supercapacitors. The $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_2\text{N}$ hybrid electrode exhibits a significantly higher capacitance and a much better rate capability than those of the $\text{Ti}_3\text{C}_2\text{T}_x$ electrode. The ex-situ XRD and XPS analyses combined with the first-principles calculations unveil the $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_2\text{N}$ interface with enhanced charge transfer capability. The symmetric supercapacitor assembled from the $\text{Ti}_3\text{C}_2\text{T}_x/\text{Ti}_2\text{N}$ hybrid electrodes with activated carbon as the counter electrode exhibits superior stability and energy storage performance. In another example, the $\text{WS}_2/\text{Ti}_3\text{C}_2\text{T}_x$ hybrid with TiO_2 nanograins at the interface demonstrates an enhanced charge-separation ability for Sono photocatalytic nitrogen fixation and pollutant degradation. Compared to MXene- WS_2 or standalone materials, the MXene/ TiO_2/WS_2 system increased both ammonia synthesis and tetracycline breakdown significantly. In visible light and ultrasound-assisted reactions the interfacial Schottky junction increases the carrier transfer, which leads to higher efficiency [197].

The MnO_2 electrodes supported on $\text{Ti}_3\text{C}_2\text{T}_x$ displayed a significantly improved capacitive performance. The ambient-pressure room-temperature method can prepare $\text{MnO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ composites with different contents of MnO_2 . The optimized $\text{MnO}_2@\text{Ti}_3\text{C}_2\text{T}_x$ (6) composite exhibited a high specific capacitance of 324.1 F g^{-1} and a decent capacitance retention of 67% at a large current density. The assembled asymmetric capacitor was delivered an energy density of 30.8 Wh/kg and power density of 7493 W/kg with 96% capacitance retention after 2000 cycles. This method is also scalable for the next-generation energy storage applications [198]. The $\text{SnO}_2/\text{ZnO}/\text{Ti}_3\text{C}_2\text{T}_x$ composite prepared by hydrothermal method also displayed an enhanced sensing performance toward ethanol gas. The sensor with 3 wt % $\text{Ti}_3\text{C}_2\text{T}_x$ content showed the maximum response (121.1) and the shortest response time (3 s), which was significantly better than that of the pure components. Benefiting from the excellent dispersion and higher response (14.4) of few-layer MXene, the $\text{ZnO}/\text{Ti}_3\text{C}_2\text{T}_x$ composite also exhibited a good sensing performance to

acetone, suggesting its potential application in gas sensing devices [199].

6.2.3 Plasmonic Metal-MXene Hybrids

The integration of plasmonic metal (e.g., Au or Ag) with MXene enables the enhanced optical and catalytic properties via localized surface plasmon resonance. For example, the Au nanoparticles ($\sim 10 \text{ nm}$) loaded on $\text{Ti}_3\text{C}_2\text{T}_x$ yield a 2.5-fold increase in the catalytic current compared to that of the MXene. This enhancement arises from the hot hole injection and Schottky junction effects. Plasmonic metal/MXene hybrids possess great potential for the modulated MXene heterostructure design for efficient oxygen evolution reaction [200]. In photocatalysis, core-shell $\text{Au}@ \text{ZnIn}_2\text{S}_4$ nanostructures anchored on $\text{Ti}_3\text{C}_2\text{T}_x$ enable efficient hot-electron transfer. The structured interface ensures sequential charge flow from Au to ZIS to MXene. This tandem enhances PEC seawater splitting, delivering the highest photocurrent and reduced charge resistance while boosting H_2 generation by 6.5 to 10.8 orders compared to reference systems. Other work used Ag- Ti_3C_2 hybrids without coating to stabilise plasmonic silver nanoparticles. The clean interface promotes charge separation and dramatically improves photocatalytic degradation of methyl orange from 1% to 96.5%. The MXene support helps maintain hot-carrier flow and suppress recombination [201]. Using electrostatic self-assembly, research groups formed uniform hot-spot substrates by mixing positively charged AgNPs with negatively charged $\text{Ti}_3\text{C}_2\text{T}_x$. This approach achieved a surface-enhanced Raman spectroscopy (SERS) factor of 3.8×10^8 . The substrate identified biomarkers such as ATP and folic acid at very low concentrations ($\sim 10^{-9} \text{ M}$ and 10^{-3} M), attributed to the interplay of electromagnetic and chemical enhancements at the MXene-Ag interface [202].

6.3 Aerogels, Foams & 3D Printed Architectures for Flow-Through Devices

Three dimensional MXene frameworks help overcome restacking of nanosheets and improve mass transport in bulk systems. Custom three dimensional printed MXene aerogels, combining macro-level design with micro-architecture, offer simple fabrication, flexible geometry, and enhanced electrical or electrochemical properties [203].

6.3.1 MXene Aerogels and Hydrogels

The MXene aerogels, which form a 3D interconnected continuous nanosheet structure, not aggregated and preserve the morphology of the initial material. The increasing problem of electromagnetic interference (EMI) and the threat of fire requires materials for EMI shielding with a low density that are non-flammable. $\text{Ti}_3\text{C}_2\text{T}_x$ has one of the highest

conductivity and one of the most favorable aspect ratios. The aerogel based on cellulose nanofibers, ammonium polyphosphate and $\text{Ti}_3\text{C}_2\text{T}_x$, synthesized by the method of freeze-drying, upon exposure to an open flame did not burn, and showed EMI shielding performance of ~ 55 dB at a thickness of 8 mm, mainly due to the absorption mechanism. The conductive properties of the material (the conductivity was ~ 12 S/m) and its voluminous structure ensure this performance [204]. The use of MXene aerogels is of interest as flexible pressure sensors with a high surface area and good conductivity, but the lack of mechanical strength at low densities is a drawback. For the first time, using MXene, polydopamine-modified SiO_2 nanofibers and silane monomers, a covalent cross-linked aerogel was created with a record-high sensitivity (-0.83 kPa $^{-1}$), a short response time (48 ms), a strain level of 1% for long-term stable sensor operation, resistance to mechanical strains for more than 10,000 cycles, and is promising for use in health monitoring devices [205].

A biomass-derived carbon aerogel obtained by loofah carbonization and $\text{Ti}_3\text{C}_2\text{T}_x$ impregnation showed excellent adsorption capacity for dyes and pharmaceuticals with the maximum adsorption of 175 mg/g for methylene blue and a good adsorption performance for Rhodamine B, methyl orange, Congo red and tetracycline. The obtained aerogel obeyed Langmuir adsorption isotherm model and pseudo-second-order kinetic model. The adsorbent was regeneration capable after multiple adsorption-desorption cycles. In general, the 3D porous MXene architectures obtained by freeze-drying, spray drying, templating, gas foaming or 3D printing process could provide an enhanced ion transport and expose more surface area, which are potential for energy storage devices, batteries, electrocatalysis, and electrosorption; while the challenge is the fabrication of large-scale and controlled properties of MXene structures [206].

6.3.2 Composite Aerogels and Functional Integration

Composite aerogels based on MXene and polymer exhibit multimodal performances and maintain the 3D architecture. A CNF/ $\text{Ti}_3\text{C}_2\text{T}_x$ /PVA aerogel was prepared by bidirectional freezing and vapor deposition and showed an ultralow density, good compressibility, and conductivity. The resulting material was modified by polysiloxane coating to make it hydrophobic, which enabled the aerogel to have a large uptake capacity (30–167 g/g) for organic pollutants (e.g., oil and solvent) with superb recyclability. The developed material was also applied as a pressure sensor, which exhibited an outstanding sensitivity of 2.41 kPa $^{-1}$ and rapid response/recovery time (78 ms / 83 ms) for detecting human motion [207].

For the development of certain catalytic and sensing capabilities, Incorporation of nanoparticles into

MXene aerogels is needed. The MXene aerogels with Pt or Pd anchoring on $\text{Ti}_3\text{C}_2\text{T}_x$ exposed the formation of layered network structures, which could serve as an efficient catalyst for gas-phase hydrogenation reactions. The synthesis approach affects the surface morphology and the distribution of the metal. Pt single-atom catalysts supported on MXene showed excellent selectivity in butadiene hydrogenation reaction and near 99% selectivity in CO_2 reduction reaction to CO, which was better than that of the oxide-supported counterparts. $\text{SnO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ aerogels also demonstrated an amazing H_2S sensing performance. The obtained composite was prepared by solvothermal and annealing methods. The sensitivity value of the material reached 150 at 30 ppm H_2S , which was significantly higher than that of the pure SnO_2 . It is worthy of note that the composites had a p-n junction structure and a large surface area, making the detection limit of the material as high as ~ 5.76 ppb. The results were further revealed by the first-principles study of adsorption energy [208].

6.3.3 3D Printing and Additive Manufacturing

Additive manufacturing can precisely design MXene aerogels according to the intended performance. For advanced energy storage devices, direct ink writing (DIW) has become one of the possible and easiest way to create three dimensional electrodes. The printed anode (Ag NPs@ Ti_3C_2) provided ~ 369 F/g at 1 A/g, and MnO_2 @ Ti_3C_2 cathode ~ 474 F/g. An all-printed, asymmetric supercapacitor showed ~ 38.2 Wh/kg energy density at 800 W/kg power with $\sim 91\%$ capacitance retention over 5000 cycles. Rheological tuning and cross-linkers improve print quality, and aerosol jet printing of an MXene sodium alginate composite on chitosan enabled flexible sensors sensitive to temperature and humidity. MXene/SA@CS sensor showed real-time response to human activities, temperature resistance coefficient of 1.08%/°C and antibacterial properties, and was used as a non-contact interface to control fingers [209]. 3D-printed MXene electrodes can be useful for battery production due to their low-cost and less-wasteful structures. Due to the complexity of the materials preparation methods the performance of the printed electrodes varies. The selection of the right materials and printing methods affects the outcome of the printed battery electrodes since not all materials are compatible with the standard 3D printing techniques. Therefore, it is needed to pay attention to the choice of additives and post-processing to achieve the desired characteristics of energy storage devices [210].

6.3.4 Flow-Through Environmental Remediation Systems

Monolithic MXene aerogels serve as efficient flow-through remediation supports. One study utilized MXene aerogels cross-linked by Al^{3+} and freeze-dried to

host polyethylene glycol phase change materials (PCMs). The aerogel accommodated up to 97 wt% PEG, retained ~90-96 % latent heat over the loading range, resisted leakage above 60°C, and maintained heat storage performance over 500 cycles. Solar energy utilisation reached ~93.5 %, outperforming many reported systems [211]. A solar steam evaporator built from Ag-MXene integrated into chitosan hydrogel offered antibacterial water purification. The 3D AM/CH evaporator effectively killed *E. coli* and *S. aureus* under solar irradiation, achieving an evaporation rate of ~1.59 kg m⁻²h⁻¹ at approximately 93% efficiency and removing dyes and salts efficiently through multiple cycles. These self-cleaning properties make it ideal for clean water applications. A low-cost, safer titanium-based MXene synthesized from activated charcoal and molten salt offers effective VOC adsorption. Although its carbon form differs from graphite-based MXene, both remove over 80 % contaminants. The activated-carbon-derived MXene is cheaper and more regenerable. Its simpler production and oxidation resistance suit clean water recovery applications [212].

6.3.5 Advanced Manufacturing and Scalability

To scale up 3D MXene structures, reliable, cost-effective fabrication methods with quality control are essential. The unidirectional freeze casting process allows producing structured porous aerogels from Ti₃C₂T_x flakes, which are bendable up to ~50 % of the compressive strain and maintain their conductivity upon multiple cycles. Using such aerogels as an electrode material in lithium ion capacitors, a high capacity of ~1210 mAh/g at a low current and ~200 mAh/g at a higher rate with a good cycling stability was obtained [213]. This indicates that the processing optimization can lead to the enhancement of the material's structural properties, mechanical performance and electrochemical performance, contributing towards flexible sensors and flexible energy devices.

6.4 Emerging Hybrid Architectures and Future Directions

The MXene-based composites are being developed as multifunctional hierarchical structure systems exhibiting combined functionalities at distinct hierarchies [178]. In fact, following the design principles at a range of length scales, a number of advanced MXene composites have been suggested for diverse applications [178]. In particular, inspired by natural structures, smart actuators with both flexibility and durability have been fabricated, including the recently developed humidity-driven MXene-based actuator, which consisted of carboxymethyl cellulose (CMC), MXene nanosheets, and multivalent aluminium ions (Al³⁺). The obtained MXene film with an ordered hierarchical structure similar to that of nacre was manufactured through a facile evaporation-induced self-

assembly method. The ionic interactions and hydrogen bonding between MXene and Al³⁺, along with a dense microstructure, give the composite film outstanding toughness (7.95 MJ/m³), tensile strength (273.6 MPa), and high wet strength (154.2 MPa) at 97% RH. The quick actuation (bending in 2.3 s) and outstanding durability (> 1500 cycles) of the MXene film actuator were achieved simultaneously due to the combination of the lamellar structure and humidity-induced swelling of CMC and MXene. The MXene film actuator was used to power various artificial devices, such as artificial muscle, dragonfly wings, and human fingers imitating, as well as moisture-electric generator. These examples represent a variety of promising strategies for creating multifunctional materials with complex structures and new functionalities for flexible electronics, biomorphic actuators, and soft robotics [214].

New MXene-based materials are suggested to be used as gas barrier coatings. Due to the natural negative charge of MXene layers, the application of the polymer with the same polarity is restricted. The research has shown that the creation of a multilayer film using PAA and MXene bound by hydrogen bonds at an acidic pH is a feasible method. The obtained material has a structure similar to nacre, which is uniform and does not have any defects. The hydrogen gas permeability of PAA/MXene films is 0.14 ± 0.01 cc·mm·m⁻²·day⁻¹·MPa⁻¹, which is almost 9000 times lower than that of the niobium substrates. At the same time, the films are conductive (up to 370 ± 30 S/cm) and sensitive to pH. Due to the possibility of hydrolysis in a base, they can be used as pH sensors, or flexible electronics [215].

Nowadays, the process of machine learning is implemented to rapidize the design of MXene-based composites. In recent study authors proposed a neural network model that predicts the electromagnetic interference (EMI) shielding performances of aerogels made of silver-modified zinc oxide, waterborne polyurethane, and barium ferrite. Sixteen aerogels' samples were prepared by pre-casting and directional freezing procedures. The model demonstrated excellent agreement with the experiment (the correlation coefficient was 0.9885), while for new samples the prediction error was less than 5%. In addition, the model utilized a multimodal fusion framework that combined fully connected and residual network models with Gated Fusion, achieving a high EMI shielding effectiveness performance (up to 78.6 dB) and absorption coefficient (up to 0.96). An effective way to develop new materials with high EMI shielding effectiveness is the combination of experimental work and computer modeling [216]. In general, MXene hybrid architectures are promising materials that can be applied in a variety of areas from sensors and actuators to energy and environment. Therefore, for the complete realization of their commercialization, it is necessary to optimize the preparation process, find a reliable method for preparing

composites with high consistency, and apply a data-driven design to develop high-performance materials for sustainable technologies [217].

7. Challenges and Future Perspectives

In the last decade, MXenes have shown great potential in a wide range of energy and environmental applications. Despite the higher level of interest in various fields, still some challenges that limit the commercialization and large-scale production of MXenes. In this regard, the purpose of this section is to highlight the challenges and discuss future perspectives that MXenes might encounter on the way to being an integral part of commercial devices. A comprehensive outlook on the challenges and opportunities for MXenes is presented in Figure 6.

7.1 Oxidative Stability and Shelf Life

A significant limitation for the practical implementation of MXenes beyond academic laboratories is their tendency to oxidize upon exposure to air. The presence of surface terminations, such as -O, -OH, -F, renders these materials highly susceptible to oxidation. Oxidation occurs by the attack of atmospheric oxygen and water molecules to the MXene flake edges, resulting in the gradual formation of titanium dioxide, which degrades the structure of the material. It was found by Shekhirev *et al.* (2021) that $\text{Ti}_3\text{C}_2\text{T}_x$ dispersions lost almost 70% of their electrical conductivity upon standing in ambient conditions for a week due to oxidation of the defects and edges [218]. While the majority of the prior work has been conducted on $\text{Ti}_3\text{C}_2\text{T}_x$, only several studies have targeted the XPS spectral fitting procedures. Discrepancies in the fitting protocols of $\text{Ti}_3\text{C}_2\text{T}_x$ spectra prompted a critical review that proposed a fitting procedure for the analysis of the $\text{Ti}_3\text{C}_2\text{T}_x$ composition [64].

To overcome the stability problem, researchers have recently carried out many studies using various HF concentrations during the synthesis to investigate the influence of different surface terminations on the MXene stability and conductivity. It has been found that increasing the concentration of OH-rich surface terminations provides a more thermodynamically stable structure compared to other surface terminations. Additionally, the surface dipole generated by the localized electrons on the hydroxyl group promotes further chemical reactions. The electrical conductivity of MXene strongly depends on the ratio of -O, -OH, and -F functional groups. Notably, the work function can be tuned by engineering the surface terminations, which has been predicted to vary in the range of $\Delta\Phi \sim 3.5$ eV [219]. Another approach to passivate MXene is the use of antioxidant molecules. The capping $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets with sodium ascorbate during the synthesis yields highly oxidation-resistant SA-MXene, which remains stable for more than 80 days in the air with no significant change in conductivity. Meanwhile, the as-synthesized SA-MXene demonstrates excellent performance in a micro-supercapacitor. By using a printable ink consisting of SA-MXene and additives such as Triton X-100 and propylene glycol, solid-state micro-supercapacitors were fabricated without a current collector, exhibiting outstanding capacitance [220].

7.2 Green, Scalable, and Fluoride-Free Synthesis

Early MXene synthesis procedure typically relied on HF, posing major safety risks due to its high toxicity and producing large amounts of fluorinated waste that undermines sustainability. New fluoride-free approaches to MXene preparation have been developed.

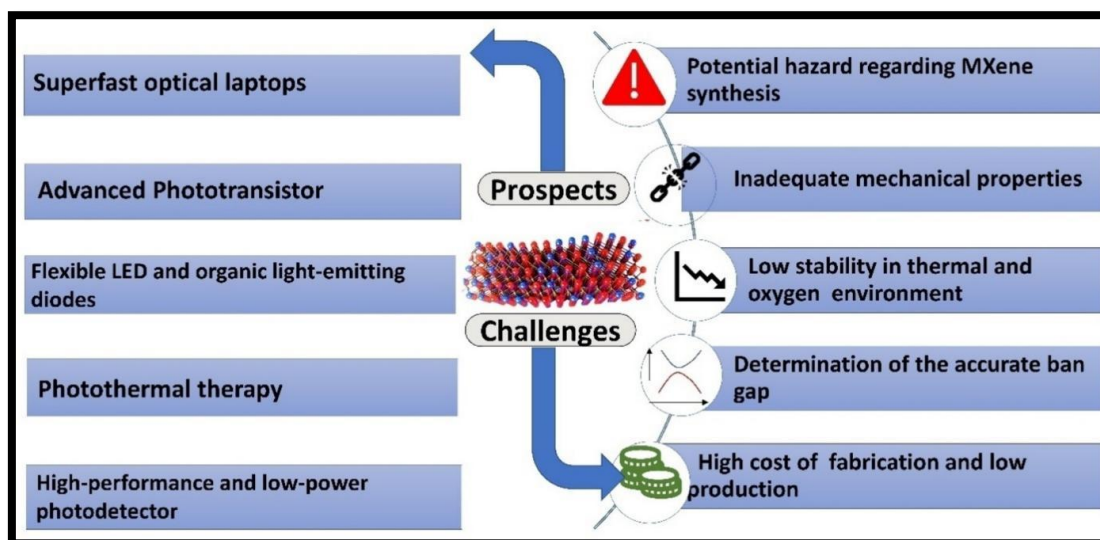


Figure 6. Schematic representation of various prospects and challenges of MXenes.

Moreover, the synthesis of MXenes, including HF etching, are associated with CO₂ emissions and high energy inputs. For instance, while preparing MXenes in laboratory conditions, a carbon footprint (CO₂ emissions) of 428.10 kg CO₂ per kg is reported, which is significantly higher than CO₂ emissions during the production of traditional materials such as aluminium and copper foils. Green synthesis approaches such as electrochemical etching using NH₄F allow for reducing the amount of chemical waste and reusing electrolytes, thus reducing the impact on the environment [221]. Molten salt-assisted electrochemical etching avoids fluorine-based etchants, enables salt recycling, and supports the development of sustainable environment. Notably, one of the approaches to electrochemical etching uses the concept of redox control of etching and does not require the use of fluorine-containing etchants. Moreover, the method has allowed preparing MXenes from rarely studied MAX phases containing, among other things, Si, Zn, and Ga. According to the example of Ti₃C₂ prepared using this technology, it is possible to obtain materials with a lithium-ion storage capacity of 205 mAh/g, demonstrating promising results for charge-discharge processes when using carbonate electrolytes [35]. However, this procedure requires high temperatures to etch the precursor, potentially causing thermal-stress defects and limiting the choice of materials.

Moreover, several synthesis parameters affect the overall yield of MXenes such as the choice of etching agent and specific synthesis conditions. The optimization of this parameter is significant because it directly determines the application of MXenes in industrial production. In addition, synthesis using fluoride allows obtaining MXene sheets with high thickness and quality. At the same time, the use of a method without fluorine leads to low yield and low quality [222]. The yield is a significant indicator in this context because anhydrous synthesis has demonstrated a record yield of more than 70% and high electrical conductivity, which indicates the possibility of obtaining high-quality MXenes [223]. These synthesis techniques yield enhanced quality of MXenes quickly and with increased efficiency, enabling industrial-scale production while preserving strong electrical properties. High-performance MXenes using a mixture of hydrofluoric and hydrochloric acids as an etchant can reach electrical conductivities of 21,000 S/cm, although the yield in this case was only 38% [223].

Moreover, several synthesis parameters affect the overall yield of MXenes such as the choice of etching agent and specific synthesis conditions. The optimization of this parameter is significant because it directly determines the application of MXenes in industrial production. In addition, synthesis using fluoride allows obtaining MXene sheets with high thickness and quality. At the same time, the use of a method without fluorine leads to low yield and low quality [222]. Electrochemical etching represents another approach using dilute hydrochloric acid to etch Ti₂AlC into Ti₂CT_x

without fluorides. While safer, this approach still encounters challenges, such as undesired carbon phases caused by over-etching, and a core-shell model was proposed to rationalize the over etching behavior [209]. More recently, ionic liquids have garnered attention; [EMIM]Cl with AlCl₃ was demonstrated to efficiently etch Ti₃AlC₂ at 180°C to obtain high-quality MXene flakes, and the ionic liquids were recyclable, thus endowing this approach with advantages of low-cost and environmental friendliness [224]. Nevertheless, such approaches still suffer from long processing time compared to that of HF-based methods and less delaminated MXene flakes. There are some drawbacks in the industrial application of MXenes such as large-scale and rapid preparation. There is an urgent need to optimize the preparation process to enhance the mechanical properties and stability of the obtained MXene to enable its extensive application. Apart from the drawbacks, MXenes has other attractive properties, including mechanical stability and excellent conductivity, enabling their potential as industrial materials for applications in energy storage and conversion [225]. It is of particular interest to further optimize such approaches and perform a cost-benefit analysis, particularly in terms of continuous-flow strategies.

As MXenes make their way to commercial use, their complete implications on the environment and human health must be considered. At the moment, very little is known about the overall energy consumption and emission rates that are characteristic for the fabrication of these materials. A cradle-to-gate life-cycle assessment was carried out in order to analyze the environmental impact of Ti₃C₂T_x production. It was found that in terms of CO₂ emission, the fabrication process of this 2D material is significantly worse than in the case of aluminium and copper foils currently used for EMI shielding applications [221]. Specifically, the production of 1 kg of MXene results in 428.10 kg of CO₂ emission in laboratory conditions, which is several times higher than the values of 23.0 and 8.75 kg for producing the same amount of aluminium and copper, respectively. One of the main reasons is the high consumption of electricity during the fabrication process, but with the use of recycled materials and renewable energy sources the usage of electricity can be minimized.

One of the reviews on MXene synthesis strategies, emphasize their importance in designing carbon capture materials, and discussed the possibility of using MXene-based materials to create efficient CO₂ adsorbents. For instance, preparing MXenes by molten salt etching generates materials with a better control of the terminal functional groups, which provides the possibility of tuning their properties [226]. On the other hand, the review underlined that MXene-based composites' recyclability is a serious challenge since strong bonding between MXene and polymer takes place, hindering the separation process at the end of the material's life cycle. MXene/MWCNT membranes for

oil/water separation showed remarkable performance in terms of flux and rejection, with some of them reaching an unprecedented level of separation. Nevertheless, the membranes suffered from fouling when exposed to viscous oils; however, an innovative photothermal cleaning approach was used to solve the problem.

By generating local heating, it was able to regain over 60% of its flux and constantly maintain a 99% rejection. It has been proved to be an excellent strategy for long-term and sustainable application. Apart from the electronic properties of MXenes, their effects on organisms have not been investigated thoroughly. A recent work evaluated the cytotoxicity of Ti_3C_2 to neural stem cells, and the results revealed that Ti_3C_2 showed no adverse impact on cell viability at a concentration of 12.5 $\mu\text{g/mL}$, while a significant cytotoxicity was observed at 25 $\mu\text{g/mL}$, as evidenced by the altered gene expression related to stress response and inflammatory cytokine [227]. Furthermore, MXenes toxicity should be noted, which can be mitigated through suitable biocompatible encapsulation while maintaining their inherent performance. There are ongoing efforts to establish the standardized safety test for 2D materials, and several governments and agencies, including OECD and ISO are working on this issue. Future works are based on designing MXenes with low-toxicity and develop systematic risk assessment methods for various applications.

7.4 Standardization: Data Repositories and Reporting Guidelines

The field of MXene research has recently experienced a rapid increase in interest, yet there is a lack of consistency in the field due to the prevalence of varying approaches to synthesis, testing, and characterization. This issue has hindered the development of the materials to their full potential and the transition to practical applications. Fortunately, it seems as though the scientific community has recognized this problem, and several initiatives have been made to standardize the production and evaluation of MXenes. More specifically, efforts by the International MXene Consortium have led to the establishment of guidelines for the synthesis of MXenes, such as the recommended HF concentrations, etching times, and washing and storing protocols. These have been adopted by more than two hundred research facilities around the globe and have contributed to the observed improvement in the reproducibility of key characteristics, including conductivity and capacitance. Additionally, a series of recommendations and guidelines for the characterization of MXene materials has been proposed [228].

Their recommendations concern the preparation of the samples, the diffraction parameters, the fitting of the peaks, and the analysis of the images. They help to avoid errors associated with oxidation or

misinterpretation of the spectra and enable the comparison of the results. In addition, standard conditions for testing are necessary to evaluate the properties of MXenes, most of which are related to energy storage. Gogotsi *et al.* (2023) suggested performance criteria relevant to all the aforementioned areas, outlining the conditions under which capacitance, cycling stability, and conductivity should be measured [229]. For example, the suggested test conditions may standardize the scan rate, voltage range, and electrolyte formulation and statistical analyses. Also, the creation of web-based tools that can share and analyze experimental data more efficiently and quickly. Some of these tools include Materials Data Facility and MXene Database that hold more than 25,000 datapoints [230]. These databases can store information needed to predict properties and guide synthesis using machine learning and advanced analytics. However, broader implementation of FAIR (Findable, Accessible, Interoperable, and Reusable) principles is needed to increase the value of open-access databases.

7.5 Emerging Frontiers

7.5.1 Twisted-Bilayer MXenes

Twisted bilayer graphene has unique electronic properties, which has inspired researches to explore the potential of angular misalignment in MXenes. More recently, theoretical calculations have been conducted to unveil the possibility of generating new electronic and optical properties of bilayer MXene systems. It was found that the twist of Ti_2C or Ti_2CO_2 sheets with MoS_2 sheets could significantly change the ion adsorption and diffusion properties. These Moiré superlattices showed angle-dependent capacity and ion diffusion barrier for alkali metal ions, such as Li, Na, and K, with the theoretical capacity as high as 500 mAh/g for Li and 223 mAh/g for K [231]. The realization of such structures with designed twist angle in experiments, however, is still a great challenge due to the complexity in controlling the oxidation of MXenes. In another work, first-principle calculations were performed to study the optical properties of twisted Ti_3C_2 bilayers. It was found that the twist angle could tune the optical properties of MXene, and the interfacial electron transfer was significant, while the infrared plasmon dispersion remained robust at different twist angles [232]. These findings provide a foundation for the prospective integration of MXenes into optoelectronic device applications.

7.5.2 MXene Quantum Dots

MXene quantum dots (MQDs) offer new possibility in photocatalysis, sensing and imaging. Different from their two-dimensional form, MQDs show the quantum confinement effect which could be manipulated through careful designing during the synthesis process. A recent article reported that Ti_3C_2

MQDs coupled with silicon carbide could remove 74.6% of NO gas under visible light irradiation, which was much better than using single materials [233]. The enhanced performance of this QD material resulted in the improved charge transfer and light-harvesting ability. In the biomedical field, MQDs exhibited great potential in sensing of glutathione in cancer cells. In a water solution, N- Ti_3C_2 QDs functionalized with Fe^{3+} ions showed sensitive fluorescent response to different concentration of glutathione with a low detection limit ($0.17 \mu\text{M}$) [234]. This method enabled novel imaging and diagnostic devices; however, further work is needed to investigate MQD stability and structure property relationships for practical applications.

7.5.3 Machine Learning-Guided Design

MXenes have a fantastic variety of possible composition and structure. The conventional method of trying every option in sequence is time requiring and it cannot be applicable. Whereas, more focus and time should be spent on increasing the yields rather than focusing on unpromising paths. It is machine learning that enables one to process the information about previously conducted experiments in order to not merely predict some properties of the materials but prioritize the research agenda. For instance, using different algorithms, one can perform tens of thousands of

reactions per day, obtain and process the results, and modify the reaction conditions in order to improve the yield or selectivity. Notably, neural networks trained on the MXenes data sets better than 15% of the time successfully predict the important characteristics of the material, such as its conductivity and capacitance [235]. Thus, machine learning can be used to prioritize research in various directions.

7.5.4 Bio-MXenes

In addition to the aforementioned fields, researchers have also applied MXENE in biology; owing to their hydrophilic surfaces, excellent conductivity, and flexibility, MXenes are promising candidates for medical purposes. For example, composite fibers composed of polycaprolactone and MXenes showed improved cell compatibility with both fibroblasts and pre-osteoblasts [236]. Bio-MXenes has a greater potential application in wound healing and tissue engineering. But the use of these materials in medical electronic devices exhibits significant enhanced signal recording capabilities for $\text{Ti}_3\text{C}_2\text{T}_x$ electrodes when compared to conventional metallic electrodes. In one of the studies, a low-cost electrode fabricated from MXene films and a cochlear implant was observed to effectively stimulate neurons while improving the cellular growth and controlling the calcium signal in neurons [237].

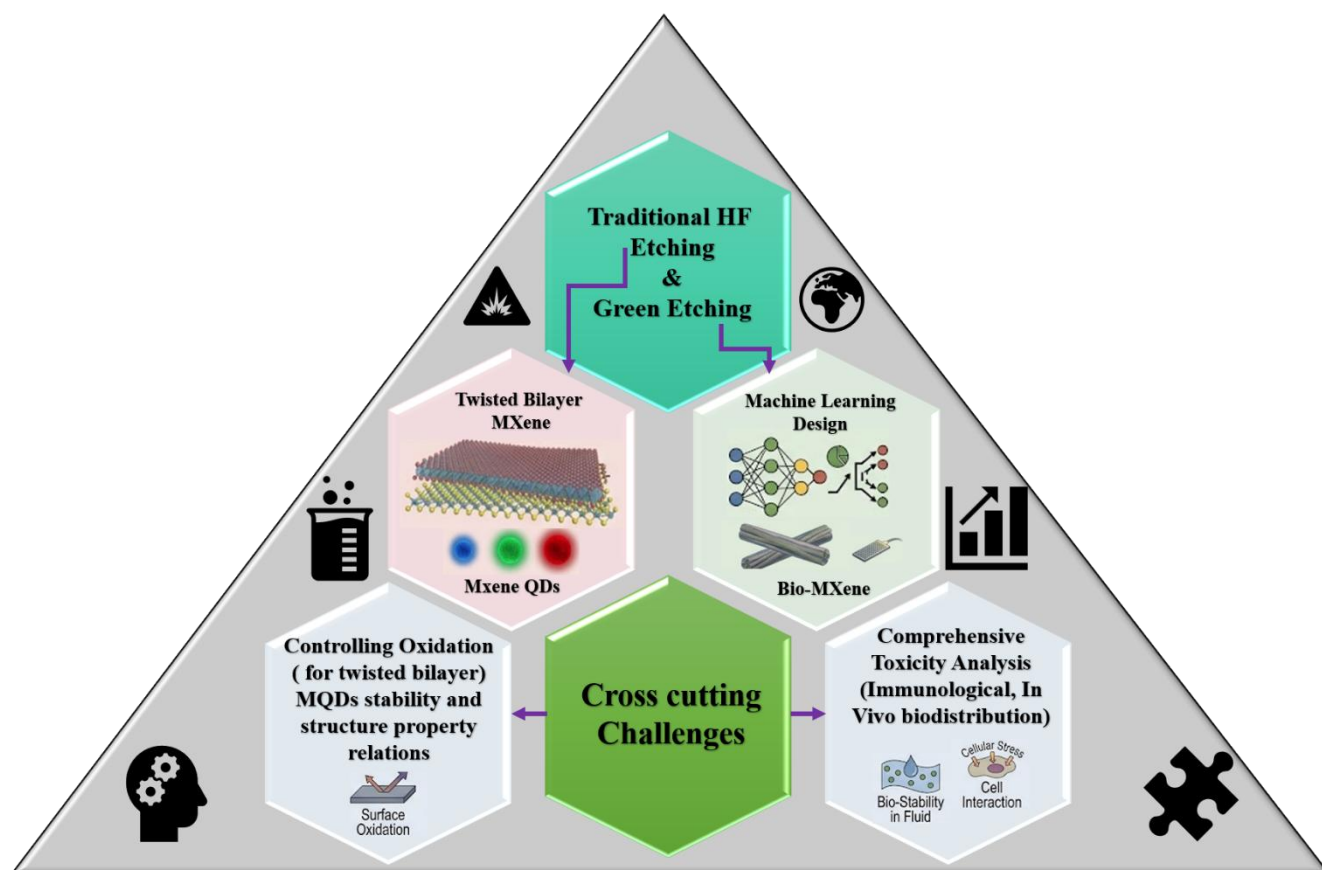


Figure 7. Schematic overview of challenges related to traditional HF and green etching process.

Due to the softness of the MXene materials, the application of such flexible and stretchable electrodes would lead to reduced damage and inflammation compared to rigid metallic electrodes. MXenes were also considered good candidates for disease diagnosis, as an electrochemical immunosensor based on AgNPs-MXene and a CA-19-9 antibody showed remarkable sensitivity with a detection limit of 1 nU/mL [238]. The immunosensor platform showed satisfactory repeatability and has the potential to be utilized in the diagnosis of pancreatic cancer. Although the abovementioned research results showed the promising potential of MXenes in the medical field, comprehensive toxicity analyses, including immunological evaluations and in vivo biodistribution studies, are critical to ensure the safety of these materials before any clinical application. The development of MXenes is now entering a new era, in which the opportunities and challenges coexist as shown in Figure 7. On the one hand, the preparation, properties, and applications of MXenes require extensive research work to overcome existing obstacles. Growing demand for material-characterization tools and methods is enabling the development of innovative materials and devices. With coordinated research and standardized frameworks, MXenes are poised to drive sustainable materials and technologies for decades.

8. Conclusion

MXenes have attracted considerable research interest among the family of two dimensional with unique combination of hydrophilic nature and metallic conductivity, along with their unique surface terminations and excellent electrochemical properties. The main aim of this review is to summarize the recent developments regarding the surface modification, structure, and synthesis of MXenes and exploring their promising applications in environmental protection and energy storage. MXenes exhibit great potential for energy storage devices (supercapacitors, Li/Sodium metal batteries) and environmental remediation (catalyst for electrocatalytic reactions, heavy metal removal from water), which stems from their particular layered structure and large surface area, allowing easy functionalization with different elements. Despite the rapid progress in this field, there are still challenges to be addressed for the further development of MXenes, including safer and more eco-friendly methods of production, more stable chemical compositions, and systematic assessment of their environmental and biological impact. In addition, the integration of MXenes into devices needs to be better understood and controlled. Moreover, collaboration among relevant government agencies and scientists are needed to fully unlock the potential applications of MXenes. The future of MXene research is full of promise, and the development of novel methodologies, such as machine learning-assisted design, hybrid material systems, and

approaches to control and optimize their production and application, will contribute to this endeavor. Furthermore, synthesis of new hybrid materials using alternative methods of fabrication with enhanced oxidation resistance may also be critical for the practical implementation of MXenes. Overall, the scientific community should devote more effort to this field to reap the benefits of MXenes in terms of energy storage and environmental protection in the future.

References

- [1] M. Naguib, V.N. Mochalin, M.W. Barsoum, Y. Gogotsi, 25th Anniversary Article: MXenes: a New Family of Two-Dimensional Materials. *Advanced Materials*, 26(7), (2014) 992-1005. <https://doi.org/10.1002/adma.201304138>
- [2] M. Naguib, M. Kurtoglu, V. Presser, J. Lu, J. Niu, M. Heon, L. Hultman, Y. Gogotsi, M.W. Barsoum, Two-Dimensional Nanocrystals: Two-Dimensional Nanocrystals Produced by Exfoliation of Ti_3AlC_2 (*Adv. Mater.* 37(2011)). *Advanced Materials*, 23(37), (2011) 4207-4207. <https://doi.org/10.1002/adma.201190147>
- [3] M. Downes, C.E. Shuck, R.W. Lord, M. Anayee, M. Shekhirev, R.J. Wang, T. Hryhorchuk, M. Dahlqvist, J. Rosen, Y. Gogotsi, M_5X_4 : a family of MXenes. *ACS Nano*, 17(17), (2023) 17158-17168. <https://doi.org/10.1021/acsnano.3c04967>
- [4] M. Khazaei, M. Arai, T. Sasaki, C.Y. Chung, N.S. Venkataramanan, M. Estili, Y. Sakka, Y. Kawazoe, Novel Electronic and Magnetic Properties of Two-Dimensional Transition Metal Carbides and Nitrides. *Advanced Functional Materials*, 23(17), (2013) 2185-2192. <https://doi.org/10.1002/adfm.201202502>
- [5] B. Anasori, M.R. Lukatskaya, Y. Gogotsi, 2D Metal Carbides and Nitrides (MXenes) for Energy Storage. *Nature Reviews Materials*, 2(2), (2017) 16098. <https://doi.org/10.1038/natrevmats.2016.98>
- [6] L. Verger, V. Natsu, M. Carey, M.W. Barsoum, MXenes: an Introduction of their Synthesis, Select Properties, and Applications. *Trends in chemistry*, 1(7), (2019) 656- 669. <https://doi.org/10.1016/j.trechm.2019.04.006>
- [7] X. Li, Z. Huang, C.E. Shuck, G. Liang, Y. Gogotsi, C. Zhi, MXene Chemistry, Electrochemistry and Energy Storage Applications. *Nature Reviews Chemistry*, 6, (2022) 389-404. <https://doi.org/10.1038/s41570-022-00384-8>
- [8] Y. Gogotsi, B. Anasori, The Rise of MXenes. *ACS Nano*, 13(8), (2019) 8491-8494. <https://doi.org/10.1021/acsnano.9b06394>

- [9] A.M. Amani, L. Tayebi, E. Vafa, A. Jahanbin, M. Abbasi, A. Vaez, H. Kamyab, L. Gnanasekaran, S. Chelliapan, MXenes in Biosensing: Enhancing Sensitivity and Flexibility—A Review of Properties, Applications, and Future Directions. *Sensing and Bio-Sensing Research*, 47, (2025) 100732. <https://doi.org/10.1016/j.sbsr.2024.100732>
- [10] J. Zhang, N. Kong, S. Uzun, A. Levitt, S. Seyedin, P.A. Lynch, S. Qin, M. Han, W. Yang, J. Liu, X. Wang, Scalable manufacturing of free-standing, strong $\text{Ti}_3\text{C}_2\text{T}_x$ MXene films with outstanding conductivity. *Advanced Materials*, 32(23), (2020) 2001093. <https://doi.org/10.1002/adma.202001093>
- [11] N.S. Abbas, M.H. Jamil, N. Ariff, H. Sharif, P. Yan, Emerging Trends of MXene Nanocomposites in Textile Substrates for Enhanced EMI Shielding: A Systematic Review. *Advanced Materials Interfaces*, 12(14), (2025), e00484. <https://doi.org/10.1002/admi.202500484>
- [12] T. Schultz, N.C. Frey, K. Hantanasirisakul, S. Park, S.J. May, V.B. Shenoy, Y. Gogotsi, N. Koch, Surface Termination Dependent Work Function and Electronic Properties of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. *Chemistry of Materials*, 31(17), (2019) 6590-6597. <https://doi.org/10.1021/acs.chemmater.9b00414>
- [13] I. Persson, J. Halim, H. Lind, T.W. Hansen, J.B. Wagner, L.A. Naslund, V. Darakchieva, J. Palisaitis, J. Rosen, P.O. Persson, 2D Transition Metal Carbides (MXenes) for Carbon Capture. *Advanced Materials*, 31(2), (2019) 1805472. <https://doi.org/10.1002/adma.201805472>
- [14] M. Ghidui, M.R. Lukatskaya, M.Q. Zhao, Y. Gogotsi, M.W. Barsoum, Conductive two-Dimensional Titanium Carbide 'Clay' with High Volumetric Capacitance. *Nature*, (2014) 379-399. <https://doi.org/10.1038/nature13970>
- [15] M.I.H. Protyai A. Bin Rashid, A Comprehensive Overview of Recent Progress in MXene-based Polymer Composites: Their Fabrication Processes, Advanced Applications, and Prospects. *Heliyon*, 10(17), (2024) e37030. <https://doi.org/10.1016/j.heliyon.2024.e37030>
- [16] M. Boota, Y. Gogotsi, MXene-Conducting Polymer Asymmetric Pseudocapacitors. *Advanced Energy Materials*, 9(7), (2019) 1802917. <https://doi.org/10.1002/aenm.201802917>
- [17] M.R. Lukatskaya, O. Mashtalir, C.E. Ren, Y. Dall'Agnese, P. Rozier, P.L. Taberna, M. Naguib, P. Simon, M.W. Barsoum, Y. Gogotsi, Cation intercalation and high volumetric capacitance of Two-Dimensional Titanium Carbide. *Science*, 341(6153), (2013) 1502-1505. <https://doi.org/10.1126/science.1241488>
- [18] Global Energy Outlook 2024: Peaks or Plateaus? <https://www.rff.org/publications/reports/global-energy-outlook-2024/>
- [19] U.O.B. and R.B. for E. in A. and the P.O. in J. authorCorporate:UNESCO, 'The water, energy, and food security nexus in Asia and the Pacific : The Pacific', 2024, <https://unesdoc.unesco.org/ark:/48223/pf0000390821>
- [20] S. Bouckaert, A.F. Pales, C. McGlade, U. Remme, B. Wanner, L. Varro, D. D'Ambrosio, T. Spencer, (2021). Net zero by 2050: A Roadmap for the Global Energy Sector. <https://trid.trb.org/View/1856381>
- [21] L. Meng, E. Tayyebi, K.S. Exner, F. Vines, F. Illas, MXenes as Electrocatalysts for the CO_2 Reduction Reaction: Recent Advances and Future Challenges. *ChemElectroChem*, 11(5), (2024) e202300598. <https://doi.org/10.1002/celec.202300598>
- [22] Drinking water — essential quality standards | EUR-Lex'. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=legissum:4499769>
- [23] R. Levin, C.M. Villanueva, D. Beene, A.L. Cradock, C. Donat-Vargas, J. Lewis, I. Martinez-Morata, D. Minovi, A.E. Nigra, E.D. Olson, L.A. Schaidler, US Drinking Water Quality: Exposure Risk Profiles for Seven Legacy and Emerging Contaminants. *Journal of exposure science & environmental epidemiology*, 34(1), (2024) 3-22. <https://doi.org/10.1038/s41370-023-00597-z>
- [24] S.E. Taelman, J. Dewulf, T.M. Bachmann, A Comprehensive Framework Covering Life Cycle Sustainability Assessment, Resource Circularity and Criticality. *Sustainable Production and Consumption*, 45, (2024) 509-524. <https://doi.org/10.1016/j.spc.2024.01.018>
- [25] P. Mongeon, A. Paul-Hus, The Journal Coverage of Web of Science and Scopus: a Comparative Analysis. *Scientometrics*, 106(1), (2016) 213-228. <https://doi.org/10.1007/s11192-015-1765-5>
- [26] A.C. Tricco, E. Lillie, W. Zarin, K.K. O'Brien, H. Colquhoun, D. Levac, D. Moher, M.D. Peters, T. Horsley, L. Weeks, S. Hempel, PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals of Internal Medicine*, 169(7), (2018) 467-473. <https://doi.org/10.7326/M18-0850>
- [27] J. Serafin, B. Dziejarski, G. Oindo Achieng, X. Vendrell, S. Chaitoglou, R. Amade-Rovira, Comprehensive Analysis of MAX Phase and

- MXene Materials for Advanced Photocatalysis, Electrocatalysis and Adsorption in Hydrogen Evolution and Storage. *Journal of Industrial and Engineering Chemistry*, 142, (2025) 18–33. <https://doi.org/10.1016/j.jiec.2024.07.023>
- [28] T.K. Paul, M.A. Khaleque, M.R. Ali, M.A.S. Aly, M.S. Bacchu, S. Rahman, M.Z.H. Khan, MXenes from MAX Phases: Synthesis, Hybridization, and Advances in Supercapacitor Applications. *RSC advances*, 15(12), (2025) 8948–8976. <https://doi.org/10.1039/D5RA00271K>
- [29] M. Guo, G. Cao, H. Pan, J. Guo, C. Chen, B. Zhang, J. Hu, Recent progress in synthesis of MAX Phases and Oxidation & Corrosion Mechanism: A Review. *Materials Research Letters*, 12(11), (2024) 765–796. <https://doi.org/10.1080/21663831.2024.2379567>
- [30] M. Sun, W. Ye, J. Zhang, K. Zheng, Structure, Properties, and Preparation of MXene and the Application of Its Composites in Supercapacitors. *Inorganics*, 12(4), (2024) 112. <https://doi.org/10.3390/inorganics12040112>
- [31] D.D. Pathak, M. Neem, G. Kumar, B. Modak, S. Neogi, B.P. Mandal, Diamondoid Covalent Organic Framework-Mxene Composite for Cathode Host in Lithium Sulfur Battery. *Journal of Energy Storage*, 117, (2025) 116176. <https://doi.org/10.1016/j.est.2025.116176>
- [32] C. Kaplan, K. Dharmaraj, T. Schultz, L. Qin, N. Chen, D.A. Douglas-Henry, B. Schmiedecke, M. Buldu-Akturk, A. Zuber, I. Dorbandt, M. Reinhardt, Enhancing CoFe Catalysts with V₂CT_x MXene-Derived Materials for Anion Exchange Membrane Electrolyzers. *Advanced Functional Materials*, 36(21), (2026) 2503842. <https://doi.org/10.1002/adfm.202503842>
- [33] B. Gurzęda, N. Boulanger, A. Nordenstrom, C. Dejoie, A.V. Talyzin, Pristine MXene: in Situ XRD Study of MAX Phase Etching with HCl+ LiF Solution. *Advanced Science*, 11(48), (2024) 2408448. <https://doi.org/10.1002/advs.202408448>
- [34] K.E. White, Y.Z. Chu, G. Gani, S. Ippolito, K.K. Barr, J.C. Thomas, A. Weber-Bargioni, K.C. Lau, Y. Gogotsi, P.S. Weiss, Atomic-Scale Investigations of Ti₃C₂T_x MXene Surfaces. *Matter*, 7(7), (2024) 2609–2618. <https://doi.org/10.1016/j.matt.2024.06.025>
- [35] Y. Li, H. Shao, Z. Lin, J. Lu, L. Liu, B. Duployer, P. O. Å. Persson, P. Eklund, L. Hultman, M. Li, K. Chen, X. Zha, S. Du, P. Rozier, Z. Chai, E. Raymundo-Piñero, P. Taberna, P. Simon, Q. Huang, A General Lewis Acidic Etching Route for Preparing Mxenes with Enhanced Electrochemical Performance in Non-Aqueous Electrolyte. *Nature Materials*, 19(8), (2020) 894–899. <https://doi.org/10.1038/s41563-020-0657-0>
- [36] D.D. Kruger, H. Garcia, A. Primo, Molten Salt Derived MXenes: Synthesis and Applications. *Advanced Science*, 11(35), (2024) 2307106. <https://doi.org/10.1002/advs.202307106>
- [37] M.P. Bilibana, Electrochemical Properties of MXenes and Applications. *Advanced Sensor and Energy Materials*, 2(4), (2023) 100080. <https://doi.org/10.1016/j.asems.2023.100080>
- [38] S.A. Sergiienko, L. Lajaunie, E. Rodriguez-Castellon, G. Constantinescu, D.V. Lopes, N.D. Shcherban, J.J. Calvino, J.A. Labrincha, Z. Sofer, A.V. Kovalevsky, Composite MAX Phase/MXene/Ni Electrodes with a Porous 3D Structure for Hydrogen Evolution and Energy Storage Application. *RSC advances*, 14(5), (2024) 3052–3069. <https://doi.org/10.1039/D3RA07335A>
- [39] M. Jussambayev, K. Shakenov, S. Sultakhan, U. Zhantikeev, K. Askaruly, K. Toshtay, S. Azat, MXenes for Sustainable Energy: A Comprehensive Review on Conservation and Storage Applications. *Carbon Trends*, 19, (2025) 100471. <https://doi.org/10.1016/j.cartre.2025.100471>
- [40] T. Azam, M.S. Khalid, Z.S. Wu, Lewis Acid Molten Salt Synthesis of 2D MXenes with Fine-Tuned Surface Terminations for Energy Storage and Conversion. *Materials Today*, 82, (2025) 289–320. <https://doi.org/10.1016/j.mattod.2024.12.004>
- [41] M. Kulkarni, A. Lalic, R. Balu, H. Zhang, N. K. Dutta, N. Roy Choudhury, Hydrothermal Synthesis of MXenes in alkali environment and development of MXene/PEDOT: PSS Composite Electrodes for Supercapacitor Applications. *MRS Advances*, 9(17), (2024) 1310–1317. <https://doi.org/10.1557/s43580-024-00951-9>
- [42] G. Deysher, C.E. Shuck, K. Hantanasirisakul, N.C. Frey, A.C. Foucher, K. Maleski, A. Sarycheva, V.B. Shenoy, E.A. Stach, B. Anasori, Y. Gogotsi, Synthesis of Mo₄VAIC₄ MAX Phase and Two-Dimensional Mo₄VC₄ MXene with Five Atomic Layers of Transition Metals. *ACS Nano*, 14(1), (2019) 204–217. <https://doi.org/10.1021/acsnano.9b07708>
- [43] J. Xu, T. Peng, X. Qin, Q. Zhang, T. Liu, W. Dai, B. Chen, H. Yu, S. Shi, Recent Advances in 2D MXenes: Preparation, Intercalation and Applications in Flexible Devices. *Journal of Materials Chemistry A*, 9(25), (2021) 14147–14171. <https://doi.org/10.1039/D1TA03070A>

- [44] A. Bhat, S. Anwer, K.S. Bhat, M.I.H. Mohideen, K. Liao, A. Qurashi, Prospects challenges and stability of 2D MXenes for clean energy conversion and storage applications. *Npj Materials and Applications*, 5(1), (2021) 61. <https://doi.org/10.1038/s41699-021-00239-8>
- [45] A. Raman, J.S. Jayan, B D.S. Deeraj, M. Srivastava, K. Joseph, A. Saritha, Delamination of MXene using Biomolecule: An Effective Strategy toward the Utilization of Delaminated MXene as Fillers in Polymer Composites. *Polymer Composites*, 46(4), (2025) 3193–3207. <https://doi.org/10.1002/pc.29163>
- [46] K. Montazeri, H. Badr, K. Ngo, K. Sudhakar, T. Elmelegy, J. Uzarski, V. Natsu, M.W., Barsoum, Delamination of MXene Flakes using Simple Inorganic Bases. *The Journal of Physical Chemistry C*, 127(21), (2023) 10391–10397. <https://doi.org/10.1021/acs.jpcc.3c02318>
- [47] W. Liu, L. Li, C. Hu, D. Chen, G. Shen, Intercalation of Small Organic Molecules into $\text{Ti}_3\text{C}_2\text{T}_x$ MXene Cathodes for Flexible High-Volume-Capacitance Zn-Ion Microsupercapacitor. *Advanced Materials Technologies*, 7(12), (2022) 2200158. <https://doi.org/10.1002/admt.202200158>
- [48] A. Lipatov, A. Goad, M.J. Loes, N.S. Vorobeve, J. Abourahma, Y. Gogotsi, A. Sinitskii, High Electrical Conductivity and Breakdown Current Density of Individual Monolayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene flakes. *Matter*, 4(4), (2021) 1413–1427. <https://doi.org/10.1016/j.matt.2021.01.021>
- [49] C. Gao, Q. Chen, J. Feng, Z. X. Xu, Optimizing Surface Texture through Ion Induction for High Areal Capacitance and enhanced Stability in MXene Electrodes. *Advanced Functional Materials*, 35(3), (2025) 2413425. <https://doi.org/10.1002/adfm.202413425>
- [50] J. Li, M. Lu, W. Zheng, W. Zhang, Ion-Intercalation Architecture for Robust Functionalization of Two-Dimensional MXenes. *Energy Storage Materials*, 64, (2024) 103068 <https://doi.org/10.1016/j.ensm.2023.103068>
- [51] B. Anasori, Y. Xie, M. Beidaghi, J. Lu, B.C. Hosler, L. Hultman, P.R. Kent, Y. Gogotsi, M.W. Barsoum, Two-Dimensional, Ordered, Double Transition Metals Carbides (MXenes). *ACS nano*, 9(10), (2015) 9507–9516. <https://doi.org/10.1021/acs.nano.5b03591>
- [52] E. Pranada, B. Ngozichukwu, R. Yoo, D. Johnson, M.A. Barteau, A. Abdel-Wahab, A. Djire, Hydrogen Evolution and Oxygen Reduction on OH/F-Terminated Titanium Nitride Mxene Reveal the Role of the Surface Termination Group in Electrocatalysis. *ACS Catalysis*, 15(2), (2025) 982–991. <https://doi.org/10.1021/acscatal.4c05247>
- [53] J. Bjork J. Rosen, Functionalizing MXenes by Tailoring Surface Terminations in Different Chemical Environment. *Chemistry of Materials*, 33(23), (2021) 9108–9118. <https://doi.org/10.1021/acs.chemmater.1c01264>
- [54] I. Persson, L.A. Naslund, J. Halim, M.W. Barsoum, V. Darakchieva, J. Palisaitis, J. Rosen, P.O.A. Persson, On the Organization and Thermal Behavior of Functional Groups on Ti_3C_2 MXene Surfaces in Vacuum. *2D Materials*, 5(1), (2018) 015002. <https://doi.org/10.1088/2053-1583/aa89cd>
- [55] M. Tang, J. Li, Y. Wang, W. Han, S. Xu, M. Lu, W. Zhang, H. Li, Surface Terminations of MXene: Synthesis, Characterization, and Properties. *Symmetry*, 14(11), (2022) 2232. <https://doi.org/10.3390/sym14112232>
- [56] R.K. Mishra, J. Sarkar, K. Verma, I. Chianella, S. Goel, H.Y. Nezhad, Exploring Transformative and Multifunctional Potential of MXenes in 2D Materials for Next-Generation Technology. *Open Ceramics*, 18, (2024) 100596. <https://doi.org/10.1016/j.oceram.2024.100596>
- [57] E. Rems, Y.J. Hu, Y. Gogotsi, R. Dominko, Pivotal Role of Surface Terminations in MXene Thermodynamic Stability. *Chemistry of materials*, 36(20), (2024) 10295–10306. <https://doi.org/10.1021/acs.chemmater.4c02274>
- [58] M. Dahlqvist, J. Rosan, Chalcogen and Halogen Surface Termination Coverage in MXenes—Structure, Stability, and Properties. *npj 2D Materials and Applications*, 8(1), (2024) 65. <https://doi.org/10.1038/s41699-024-00502-8>
- [59] G.B. pour, L.F. aval, H. Nazarpour-Fard, Effectiveness of Nitrogen-Doping in MXene-based Composites for Supercapacitor Electrodes. *Results in Chemistry*, 13, (2025) 101965. <https://doi.org/10.1016/j.rechem.2024.101965>
- [60] M. Alhabeb, K. Maleski, T.S. Mathis, A. Sarycheva, C.B. Hatter, S. Uzun, A. Levitt, Y. Gogotsi, Selective Etching of Silicon from Ti_3SiC_2 (MAX) to obtain 2D Titanium Carbide (MXene). *Angewandte Chemie International Edition*, 57(19), (2018) 5444–5448. <https://doi.org/10.1002/anie.201802232>
- [61] J. Zhang, K.A.S. Usman, M.A.N. Judicpa, D. Hegh, P.A. Lynch, J.M. Razal, Applications of X-Ray-based Characterization in MXene Research. *Small Methods*, 7(8), (2023) 2201527. <https://doi.org/10.1002/smt.202201527>

- [62] B. Soundiraraju, B.K. George, Two-Dimensional Titanium Nitride (Ti_2N) MXene: Synthesis, Characterization, and Potential Application as Surface-Enhanced Raman Scattering Substrate. *ACS nano*, 11(9), (2017) 8892–8900. <https://doi.org/10.1021/acsnano.7b03129>
- [63] D.N.G. Krishnaand, J. Philip, Review on Surface-Characterization Applications of X-ray Photoelectron Spectroscopy (XPS): Recent Developments and Challenges. *Applied Surface Science Advances*, 12, (2022) 100332. <https://doi.org/10.1016/j.apsadv.2022.100332>
- [64] V. Natu, M. Benchakar, C. Canaff, A. Habrioux, S. Celerier, M.W. Barsoum, A Critical Analysis of the X-ray Photoelectron Spectra of $\text{Ti}_3\text{C}_2\text{T}_z$ MXenes. *Matter*, 4(4), (2021) 1224–1251. <https://doi.org/10.1016/j.matt.2021.01.015>
- [65] N. Lele, M.F. Bambo, E.M. Mmutlane, L.N. Dlamini, Construction of a Multifunctional MXene@ β -cyclodextrin Nanocomposite with Photocatalytic Properties. *Emergent Materials*, 6(2), (2023) 605–626. <https://doi.org/10.1007/s42247-023-00494-z>
- [66] T. Wu, P.R.C. Kent, Y. Gogotsi, D.E. Jiang, How water attacks MXene. *Chemistry of Materials*, 34(11), (2022) 4975–4982. <https://doi.org/10.1021/acs.chemmater.2c00224>
- [67] J. Qu, X. Liu, Recent Advances on SEM-Based In Situ Multiphysical Characterization of Nanomaterials. *Scanning*, 2021, (2021) 4426254. <https://doi.org/10.1155/2021/4426254>
- [68] N.P. Shetti, A. Mishra, S. Basu, T.M. Aminabhavi, A. Alodhayb, S. Pandiaraj, MXenes as Li-ion Battery Electrodes: Progress and Outlook. *Energy & Fuels*, 37(17), (2023) 12541–12557. <https://doi.org/10.1021/acs.energyfuels.3c01346>
- [69] J. Hu, B. Xu, C. Ouyang, S.A. Yang, Y. Yao, Investigations on V_2C and V_2CX_2 ($\text{X} = \text{F}, \text{OH}$) Monolayer as a Promising Anode Material for Li Ion Batteries from First-Principles Calculations. *The Journal of Physical Chemistry C*, 118(42), (2014) 24274–24281. <https://doi.org/10.1021/jp507336x>
- [70] H. Huang, J. Cui, G. Liu, R. Bi, L. Zhang, Carbon-Coated MoSe_2 /MXene Hybrid Nanosheets for Superior Potassium Storage. *ACS nano*, 13(3), (2019) 3448–3456. <https://doi.org/10.1021/acsnano.8b09548>
- [71] Z.U. Rehman, K. Khan, S. Yao, M. Nawaz, A. Miotello, M.A. Assiri, T. Bashir, T.L. Tamang, M.S. Javed, Recent Progress in MXene-based Materials, Synthesis, Design, and Application in Lithium-Sulfur Batteries. *Materials Today Chemistry*, 40, (2024) 102200. <https://doi.org/10.1016/j.mtchem.2024.102200>
- [72] S. Yadav, N. Kurra, Diffusion kinetics of Ionic Charge Carriers across $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-aqueous Electrochemical Interfaces. *Energy Storage Materials*, 65, (2024) 103094. <https://doi.org/10.1016/j.ensm.2023.103094>
- [73] C.E. Ren, M.Q. Zhao, T. Makaryan, J. Halim, M. Boota, S. Kota, B. Anasori, M.W. Barsoum, Y. Gogotsi, Porous Two-Dimensional Transition Metal Carbide (MXene) Flakes for High-Performance Li-Ion Storage. *ChemElectroChem*, 3(5), (2016) 689–693. <https://doi.org/10.1002/celec.201600059>
- [74] H.A. Tariq, U. Nisar, J.J. Abraham, Z. Ahmad, S. AlQaradawi, R. Kahraman, R.A. Shakoor, TiO_2 Encrusted MXene as a High-Performance Anode Material for Li-Ion Batteries. *Applied Surface Science*, 583, (2022) 152441. <https://doi.org/10.1016/j.apsusc.2022.152441>
- [75] L. Chiu, S.C. Polymers, A Poly (Ethylene Oxide)/Lithium Bis (Trifluoromethanesulfonyl) Imide-Coated Polypropylene Membrane for a High-Loading Lithium–Sulfur Battery. *Polymers*, 13(4), 2025 535. <https://doi.org/10.3390/polym13040535>
- [76] S. Li, Q. Zhang, L. Liu, J. Wang, L. Zhang, M. Shi, X. Chen, Ultra-Stable Sandwich Shaped Flexible MXene/CNT@ Ni Films for High Performance Supercapacitor. *Journal of Alloys and Compounds*, 941, (2023) 168963. <https://doi.org/10.1016/j.jallcom.2023.168963>
- [77] W. Zhang, S. Liu, J. Chen, F. Hu, X. Wang, H. Huang, M. Yao, Exploring the Potentials of $\text{Ti}_3\text{C}_2\text{N}_{2-x}\text{T}_x$ ($x = 0, 1, 2$)-MXene for Anode Materials of High-Performance Sodium-Ion Batteries. *ACS applied materials & interfaces*, 13(19), (2021) 22341–22350. <https://doi.org/10.1021/acsami.1c02470>
- [78] E. Xu, Y. Zhang, H. Wang, Z. Zhu, J. Quan, Y. Chang, P. Li, D. Yu, Y. Jiang, Ultrafast kinetics Net Electrode Assembled Via MoSe_2 /MXene heterojunction for High-Performance Sodium-Ion Batteries. *Chemical Engineering Journal*, 385, (2020) 123839. <https://doi.org/10.1016/j.cej.2019.123839>
- [79] Q. Yang, Z. Huang, X. Li, Z. Liu, H. Li, G. Liang, D. Wang, Q. Huang, S. Zhang, S. Chen, C. Zhi, A Wholly Degradable, Rechargeable Zn– Ti_3C_2 MXene Capacitor with Superior Anti-Self-Discharge Function. *ACS nano*, 13(7), (2019) 8275–8283. <https://doi.org/10.1021/acsnano.9b03650>

- [80] G. Wang, MXene-enabled Interfaces and Architectures for High-Performance Zinc Anodes in Aqueous Zinc-Ion Batteries. *International Journal of Electrochemical Science*, 20(6), (2025) 101023. <https://doi.org/10.1016/j.ijoes.2025.101023>
- [81] C. Chen, T. Wang, X. Zhao, A. Wu, S. Li, N. Zhang, X. Qu, L. Jiao, Y. Liu, Customizing Hydrophilic Terminations for V_2CT_x MXene toward Superior Hybrid-Ion Storage in Aqueous Zinc Batteries. *Advanced Functional Materials*, 34(9), (2024) 2308508. <https://doi.org/10.1002/adfm.202308508>
- [82] Y. Tian, Y. An, C. Liu, S. Xiong, J. Feng, Y. Qian, Reversible Zinc-based Anodes Enabled by Zincophilic Antimony Engineered MXene for Stable and Dendrite-free Aqueous Zinc Batteries. *Energy Storage Materials*, 41, (2021) 343-353. <https://doi.org/10.1016/j.ensm.2021.06.019>
- [83] Y. Jiang, Applications and Perspectives of $Ti_3C_2T_x$ MXene in Electrochemical Energy Storage Systems. *International Journal of Electrochemical Science*, 20(2), (2025) 100948. <https://doi.org/10.1016/j.ijoes.2025.100948>
- [84] K.Y. Zhang, H.H. Liu, M.Y. Su, J.L. Yang, X.T. Wang, E.H. Ang, Z.Y. Gu, S.H. Zheng, Y.L. Heng, H.J. Liang, Y. Wang, Defect Engineering Unveiled: Enhancing Potassium Storage in Expanded Graphite Anode. *Journal of Colloid and Interface Science*, 664, (2024) 607-616. <https://doi.org/10.1016/j.jcis.2024.03.084>
- [85] G.A. Ferrero, G. Avall, K. Janben, Y. Son, Y. Kravets, Y. Sun, P. Adelhelm, Solvent co-Intercalation Reactions for Batteries and Beyond. *Chemical Reviews*, 125(6), (2025) 3401-3439. <https://doi.org/10.1021/acs.chemrev.4c00805>
- [86] R. Akhter, S.S. Maktedar, MXenes: A Comprehensive Review of Synthesis, Properties, and Progress in Supercapacitor Applications. *Journal of Materiomics*, 9(6), (2023) 1196–1241. <https://doi.org/10.1016/j.jmat.2023.08.011>
- [87] N. Anjum, A.A. Noman, M.M. Rahman, D. Sen, R.A. Lazenby, O.I. Okoli, Electrochemical Impedance Analysis of $Ti_3C_2T_x$ MXene for Pseudocapacitive Charge Storage. *Journal of Composites Science*, 9(3), (2025) 139. <https://doi.org/10.3390/jcs9030139>
- [88] S.J. Panchu, K. Raju, H.C. Swart, Emerging Two-Dimensional Intercalation Pseudocapacitive Electrodes for Supercapacitors. *ChemElectroChem*, 11(15), (2024), e202300810. <https://doi.org/10.1002/celec.202300810>
- [89] S. Srinivasan, M. Jothibas, N. Nesakumar, Enhancing Electric Double Layer Capacitance of Two-Dimensional Titanium Carbide (MXene) with Facile Synthesis and Accentuated Properties. *Energy & Fuels*, 36(5), (2022) 2811–2820. <https://doi.org/10.1021/acs.energyfuels.1c04092>
- [90] Y. Tian, B. Que, Y. Luo, M. Ju, Y. Tang, X. Lou, Z. Chen, W. Que, Amino-Rich Surface-modified MXene as Anode for Hybrid Aqueous Proton Supercapacitors with Superior Volumetric Capacity. *Journal of Power Sources*, 495, (2021) 229790. <https://doi.org/10.1016/j.jpowsour.2021.229790>
- [91] R. Devi, V. Kumar, S. Kumar, M. Bulla, A.K. Mishra, Performance Optimization of the Symmetric Supercapacitors based on Paddy Straw-Derived Porous Activated Carbon. *Journal of Energy Storage*, 79, (2023) 110167. <https://doi.org/10.1016/j.est.2023.110167>
- [92] J. Xiao, P. Yu, K. Zhao, H. Gao, Two-Dimensional Transition Metal Carbide ($Ti_{0.5}V_{0.5}$) $_3C_2T_x$ MXene as High Performance Electrode for Flexible Supercapacitor. *Journal of Colloid and Interface Science*, 639, (2023) 233–240. <https://doi.org/10.1016/j.jcis.2023.02.068>
- [93] X. Tao, L. Zhang, X. He, L. Fang, H. Wang, L. Zhang, L. Yu, G. Zhu, Nitrogen-Doped Porous MXene (Ti_3C_2) for Flexible Supercapacitors with Enhanced Storage Performance. *Molecules*, 27(15), (2022) 4890. <https://doi.org/10.3390/molecules27154890>
- [94] J. Azadmanjiri, L. Děkanovský, Z. Sofer, Boosting Energy Storage Performance of $Ti_3C_2T_x$ Composite Supercapacitors Via Decorated Chalcogen (S, Se, Te) And New Phase-Formed Binding Sites. *Materials Today Sustainability*, 21, (2023) 100322. <https://doi.org/10.1016/j.mtsust.2023.100322>
- [95] J. Azadmanjiri, L. Děkanovský, S. Wei, M. Li, Z. Sofer, Covalent Alteration of $Ti_3C_2T_x$ MXene Layers by Selenium Decoration for enhanced Electrochemical Capacitance. *Journal of Energy Storage*, 56, (2022) 105918. <https://doi.org/10.1016/j.est.2022.105918>
- [96] S. Hussain, I. Rabani, D. Vikraman, T. Mehran, F. Shahzad, Y. Seo, H. Kim, J. Jung, Designing the MXene/Molybdenum Diselenide Hybrid Nanostructures for High-Performance Symmetric Supercapacitor and Hydrogen Evolution Applications. *International Journal of Energy Research*, 45(13), (2021) 18770–18785. <https://doi.org/10.1002/er.6998>
- [97] Z. Pan, X. Li, C. Yang, X. Ji, One-step construction of $Ti_3C_2T_x/MoS_2$ Hierarchical 3D Porous Heterostructure for Ultrahigh-Rate

- Supercapacitor. *Journal of Colloid and Interface Science*, 634, (2022) 460–468. <https://doi.org/10.1016/j.jcis.2022.12.013>
- [98] W. Hou, Y. Sun, Y. Zhang, T. Wang, L. Wu, Y. Du, W. Zhong, Mixed-Dimensional Heterostructure of Few-Layer MXene based Vertical Aligned MoS₂ Nanosheets for enhanced Supercapacitor Performance. *Journal of Alloys and Compounds*, 859, (2020) 157797. <https://doi.org/10.1016/j.jallcom.2020.157797>
- [99] A. Yadav, S. Singal, P. Soni, G. Singh, R.K. Sharma, Structural Engineering and Carbon enrichment in V2CT_x MXene: An Approach for enhanced Supercapacitive Charge Storage. *Journal of Alloys and Compounds*, 934, (2022) 167859. <https://doi.org/10.1016/j.jallcom.2022.167859>
- [100] W. Luo, Y. Sun, Z. Lin, X. Li, Y. Han, J. Ding, T. Li, C. Hou, Y. Ma, Flexible Ti₃C₂T_x MXene/V2O5 Composite Films for High-Performance All-Solid Supercapacitors. *Journal of Energy Storage*, 62, (2023) 106807. <https://doi.org/10.1016/j.est.2023.106807>
- [101] W. Luo, Y. Wei, Z. Zhuang, Z. Lin, X. Li, C. Hou, T. Li, Y. Ma, Fabrication of Ti₃C₂T_x MXene/Polyaniline Composite Films with Adjustable Thickness for High-Performance Flexible all-Solid-State Symmetric Supercapacitors. *Electrochimica Acta*, 406, (2022) 139871. <https://doi.org/10.1016/j.electacta.2022.139871>
- [102] Y. Liu, Y. Yang, B. Deng, L. Jing, B. Yin, M. Yang, Vertically Aligned Polyaniline Nano-Array Decorated on Ultra-Thin MXene Nanosheets for High Energy Density Supercapacitors. *Journal of Energy Storage*, 56, (2022) 105893. <https://doi.org/10.1016/j.est.2022.105893>
- [103] H. Xie, S. Ma, Z. He, Facile Preparation of PANI/MoO_x Nanowires Decorated MXene film Electrodes for Electrochemical Supercapacitors. *Electrochimica Acta*, 448, (2023) 142173. <https://doi.org/10.1016/j.electacta.2023.142173>
- [104] X. Liu, Z. Lu, X. Huang, J. Bai, C. Li, C. Tu, X. Chen, Self-Assembled S,N Co-Doped reduced Graphene Oxide/Mxene Aerogel for both Symmetric Liquid- and All-Solid-State Supercapacitors. *Journal of Power Sources*, 516, (2021) 230682. <https://doi.org/10.1016/j.jpowsour.2021.230682>
- [105] W. Zheng, J. Halim, P. O. Persson, J. Rosen, M.W. Barsoum, MXene-based Symmetric Supercapacitors with High Voltage and High Energy Density. *Materials Reports Energy*, 2(1), (2022) 100078. <https://doi.org/10.1016/j.matre.2022.100078>
- [106] J. Qi, H. Gu, C. Ruan, L. Zhu, Q. Meng, Y. Sui, X. Feng, W. Wei, H. Zhang, NiCo₂S₄ Decorated Multilayer Titanium Carbide MXene Electrode for Asymmetric Supercapacitor. *Ionics*, 28(6), (2022) 2979–2989. <https://doi.org/10.1007/s11581-022-04516-4>
- [107] J. Xu, X. Yang, Y. Zou, L. Zhu, F. Xu, L. Sun, C. Xiang, J. Zhang, High Density Anchoring of NiMoS₄ on Ultrathin Ti₃C₂ MXene Assisted by Dopamine for Supercapacitor Electrode Materials. *Journal of Alloys and Compounds*, 891, (2021) 161945. <https://doi.org/10.1016/j.jallcom.2021.161945>
- [108] Y. Li, S. Wang, G. Ni, Q. Li, Facile Synthesis of NiCo₂O₄ Nanowire Arrays/Few-Layered Ti₃C₂ MXene Composite as Binder-Free Electrode for High-Performance Supercapacitors. *Molecules*, 27(19), (2022) 6452. <https://doi.org/10.3390/molecules27196452>
- [109] W. Wu, T. Liu, J. Diwu, C. Li, J. Zhu, Metal-Organic Framework-Derived NiCo₂S₄@Co₃S₄ Yolk-Shell Nanocages/Ti₃C₂T_x MXene for High-Performance Asymmetric Supercapacitors. *Journal of Alloys and Compounds*, 954, (2023) 170213. <https://doi.org/10.1016/j.jallcom.2023.170213>
- [110] J. Lu, J. Wang, J. Gong, C. Hu, Design of Flower-Shaped Array of Nickel-Cobalt Nanosheets for High-Performance Asymmetric Supercapacitors. *Journal of Materials Science: Materials in Electronics*, 33(23), (2022) 18922–18937. <https://doi.org/10.1007/s10854-022-08768-8>
- [111] R.A. Chavan, G.P. Kamble, S. B. Dhavale, A. S. Rasal, S. S. Kolekar, J. Chang, A. V. Ghule, NiO@MXene Nanocomposite as An Anode with enhanced Energy Density for Asymmetric Supercapacitors. *Energy & Fuels*, 37(6), (2023) 4658–4670. <https://doi.org/10.1021/acs.energyfuels.2c04206>
- [112] Y. Pang, X. Sun, S. Guo, H. Zhu, H. Zhu, Q. Zhang, L. Wang, Inlaid Layered Double Hydroxides and MXene Composite Electrodes with High Rate Performance as Asymmetric Supercapacitors. *Journal of Materials Science: Materials in Electronics*, 34(5), (2023) 340. <https://doi.org/10.1007/s10854-022-09395-z>
- [113] J. Guo, Z. Bian, L. Ye, Y. Shang, F. Guo, Y. Zhang, J. Xu, Double Layers Combined with MXene and in Situ Grown NiAl-LDH Arrays on Nickel Foam for enhanced Asymmetric Supercapacitors. *Ionics*, 28(6), (2022) 2967–2977. <https://doi.org/10.1007/s11581-022-04520-8>
- [114] Z. Zhao, X. Wu, C. Luo, Y. Yang, High Capacitance and Cycling Stability of Flexible-

- Asymmetric-Supercapacitor based on Hierarchical NiAlP/NiAl-LDHs@MXene Electrodes. *Journal of Power Sources*, 545, (2022) 231910. <https://doi.org/10.1016/j.jpowsour.2022.231910>
- [115] J. Pan, S. Li, L. Zhang, F. Li, Z. Zhang, T. Yu, D. Zhang, Designed formation of 2D/2D Hierarchical V₂CT_x MXene/NiV Layered Double Hydroxide Heterostructure with Boosted Electrochemical Performance for Asymmetric Supercapacitors. *Journal of Energy Storage*, 55, (2022) 105415. <https://doi.org/10.1016/j.est.2022.105415>
- [116] G. Wang, G. Wang, N. Jiang, Y. Xu, Z. Zhang, G. Wang, G. Wang, K. Cheng, Solvent-Assisted Assembly of reduced graphene Oxide/MXene-polypyrrole Composite Film for Flexible Supercapacitors. *Journal of Colloid and Interface Science*, 630(Part B), (2022) 817–827. <https://doi.org/10.1016/j.jcis.2022.10.135>
- [117] L. Liu, Y. Li, Y. Zhang, X. Shang, C. Song, F. Meng, Ni₃S₂ Thin-Layer Nanosheets Coupled with Co₉S₈ Nanoparticles Anchored on 3D Cross-Linking Composite Structure CNT@MXene for High-Performance Asymmetric Supercapacitor. *Electrochimica Acta*, 439, (2022) 141694. <https://doi.org/10.1016/j.electacta.2022.141694>
- [118] X. Chen, J. Cai, C. Qiu, W. Liu, Y. Xia, High-performance solid-state asymmetric supercapacitor based on Ti₃C₂T_x MXene/VS₂ cathode and Fe₃O₄@rGO hydrogel anode. *Electrochimica Acta*, 438, (2023) 141572. <https://doi.org/10.1016/j.electacta.2022.141572>
- [119] Y. Wang, N. Chen, Y. Liu, X. Zhou, B. Pu, Y. Qing, M. Zhang, X. Jiang, J. Huang, Q. Tang, B. Zhou, W. Yang, MXene/Graphdiyne Nanotube Composite Films for Free-Standing and Flexible Solid-State Supercapacitor. *Chemical Engineering Journal*, 450, (2022) 138398. <https://doi.org/10.1016/j.cej.2022.138398>
- [120] Y. Cheng, Y. Xie, H. Cao, L. Li, L. Li, Z. Liu, S. Yan, Y. Ma, W. Liu, Y. Yue, J. Wang, Y. Gao, L. Li, L. Li, High-Strength MXene Sheets through Interlayer Hydrogen Bonding for Self-Healing Flexible Pressure Sensor. *Chemical Engineering Journal*, 453, (2022) 139823. <https://doi.org/10.1016/j.cej.2022.139823>
- [121] Pathak, D. Acharya, K. Chhetri, P.C. Lohani, T.H. Ko, A. Muthurasu, S. Subedi, T. Kim, S. Saidin, B. Dahal, H. Y. Kim, Ti₃C₂T_x MXene Integrated Hollow Carbon Nanofibers with Polypyrrole Layers for MOF-Derived Freestanding Electrodes of Flexible Asymmetric Supercapacitors. *Chemical Engineering Journal*, 469, (2023) 143388. <https://doi.org/10.1016/j.cej.2023.143388>
- [122] H. Wang, J. Li, X. Kuai, L. Bu, L. Gao, X. Xiao, Y. Gogotsi, Enhanced Rate Capability of ion-Accessible Ti₃C₂T_x-NBN Hybrid Electrodes. *Advanced Energy Materials*, 10(35), (2020) 2001411. <https://doi.org/10.1002/aenm.202001411>
- [123] M.K. Aslam, Y. Niu, M. Xu, MXenes for Non-Lithium-Ion (Na, K, Ca, Mg, and Al) Batteries and Supercapacitors. *Advanced Energy Materials*, 11(2), (2021) 2000681. <https://doi.org/10.1002/aenm.202000681>
- [124] Q. Peng, J. Zhou, J. Chen, T. Zhang, Z. Sun, Cu Single Atoms on Ti₂CO₂ as a Highly Efficient Oxygen Reduction Catalyst in a Proton Exchange Membrane Fuel Cell. *Journal of Materials Chemistry A*, 7(45), (2019) 26062–26070. <https://doi.org/10.1039/C9TA08297B>
- [125] W. Wang, N. Batool, T. Zhang, J. Liu, X. Han, J. Tian, R. Yang, When MOFs meet MXenes: Superior ORR Performance in both Alkaline and Acidic Solutions. *Journal of Materials Chemistry A*, 9(7), (2020) 3952–3960. <https://doi.org/10.1039/D0TA10811A>
- [126] M. Singh, S. Qin, K.A. Usman, L. Wang, D. Jiang, G. Yang, D. Liu, Y. Ma, W. Lei, MXene-modified Aramid Aerogel for advanced Solar Steam Generation. *Advanced Energy and Sustainability Research*, 5(1), (2023) 2300126. <https://doi.org/10.1002/aesr.202300126>
- [127] W. Han, Y. Yan, H. Wang, J. Li, P. Zhao, Z. Liu, F. Yu, J. Cui, G. Zhang, Bifunctional Photothermal Evaporator based on an MXene/Fe-MOF Collaborative effect toward efficient Solar Steam Generation and Simultaneous VOC removal. *Langmuir*, 40(41), (2024) 21767–21779. <https://doi.org/10.1021/acs.langmuir.4c02924>
- [128] R.T. Ginting, H. Abdullah, D. A. Barus, V. Fauzia, Extremely High-Efficiency Solar Steam Generation, Robust and Scalable Photothermal Evaporator based on ZIF-67@MXene/rGO Decorated Rock Wool. *Journal of Materials Chemistry A*, 11(10), (2023) 5296–5308. <https://doi.org/10.1039/D2TA09778H>
- [129] H. Shin, W. Jeong, T.H. Han, Maximizing Light-To-Heat Conversion of Ti₃C₂T_x MXene Metamaterials with Wrinkled Surfaces for Artificial Actuators. *Nature Communications*, 15(1), (2024) 10507. <https://doi.org/10.1038/s41467-024-54802-0>
- [130] A. Pandey, Shreya, P. Phogat, MXene as high-performance 2D materials for next-generation photovoltaic cells. *Sustainable Materials and Technologies*, 45, (2025) e01530. <https://doi.org/10.1016/j.susmat.2025.e01530>

- [131] L. Yang, C. Dall'Agnese, Y. Dall'Agnese, G. Chen, Y. Gao, Y. Sanehira, A. K. Jena, X. Wang, Y. Gogotsi, T. Miyasaka, Surface-Modified Metallic $\text{Ti}_3\text{C}_2\text{T}_x$ MXene as Electron Transport Layer for Planar Heterojunction Perovskite Solar Cells. *Advanced Functional Materials*, 29(46), (2019). <https://doi.org/10.1002/adfm.201905694>
- [132] J. Wang, Z. Cai, D. Lin, K. Chen, L. Zhao, F. Xie, R. Su, W. Xie, P. Liu, R. Zhu, Plasma Oxidized $\text{Ti}_3\text{C}_2\text{T}_x$ MXene as Electron Transport Layer for Efficient Perovskite Solar Cells. *ACS Applied Materials & Interfaces*, 13(27), (2021) 32495–32502. <https://doi.org/10.1021/acsami.1c07146>
- [133] A. Di Vito, A. Pecchia, M.A.D. Maur, A. Di Carlo, Nonlinear Work Function Tuning of Lead-Halide Perovskites by MXenes with Mixed Terminations. *Advanced Functional Materials*, 30(47), (2020). <https://doi.org/10.1002/adfm.201909028>
- [134] S. Palei, G. Murali, C. H. Kim, I. In, S. Y. Lee, S. J. Park, A Review on Interface Engineering of MXenes for Perovskite Solar Cells. *Nano-Micro Letters*, 15(1), (2023) 123. <https://doi.org/10.1007/s40820-023-01083-9>
- [135] P. Pandey, A. Sengupta, S. Parmar, U. Bansode, S. Gosavi, A. Swarnkar, S. Muduli, A.D. Mohite, S. Ogale, $\text{CsPbBr}_3\text{-Ti}_3\text{C}_2\text{T}_x$ MXene QD/QD Heterojunction: Photoluminescence Quenching, Charge Transfer, and Cd ion Sensing Application. *ACS Applied Nano Materials*, 3(4), (2020) 3305–3314. <https://doi.org/10.1021/acsanm.0c00051>
- [136] P. Lu, J. Wu, X. Shen, X. Gao, Z. Shi, M. Lu, W. Yu, Y. Zhang, $\text{ZnO-Ti}_3\text{C}_2$ MXene Electron Transport Layer for High External Quantum Efficiency Perovskite Nanocrystal Light-Emitting Diodes. *Advanced Science*, 7(19), (2020) e2001562. <https://doi.org/10.1002/advs.202001562>
- [137] M. T. Hossain, M. R. Repon, M. A. Shahid, A. Ali, T. Islam, Progress, Prospects and Challenges of MXene Integrated Optoelectronics Devices. *ChemElectroChem*, 11(8), (2024) e202400008. <https://doi.org/10.1002/celec.202400008>
- [138] S.G. Eswaran, M. Rashad, A.S.K. Kumar, A. F. M. El-Mahdy, A Comprehensive Review of MXene-based Emerging Materials for Energy Storage Applications and Future Perspectives. *Chemistry - An Asian Journal*, 20(4), (2024) e202401181. <https://doi.org/10.1002/asia.202401181>
- [139] M. Mishra, S. K. Behura, M. Beidaghi, K. Verma, S. Singh, MXene: A non-oxide next-generation energy storage materials for batteries and supercapacitors. In *Materials Horizons*, (2021) 73–98. https://doi.org/10.1007/978-981-16-3322-5_6
- [140] S. Bansal, P. Chaudhary, B.B. Sharma, S. Saini, A. Joshi, Review of MXenes and their Composites for Energy Storage Applications. *Journal of Energy Storage*, 87, (2024) 111420. <https://doi.org/10.1016/j.est.2024.111420>
- [141] M. Pandey, K. Deshmukh, A. Raman, A. Asok, S. Appukuttan, G. Suman, Prospects of MXene and Graphene for Energy Storage and Conversion. *Renewable and Sustainable Energy Reviews*, 189, (2023) 114030. <https://doi.org/10.1016/j.rser.2023.114030>
- [142] J. Pang, R.G. Mendes, A. Bachmatiuk, L. Zhao, H.Q. Ta, T. Gemming, H. Liu, Z. Liu, M.H. Rummeli, Applications of 2D MXenes in Energy Conversion and Storage Systems. *Chemical Society Reviews*, 48(1), (2018) 72–133. <https://doi.org/10.1039/C8CS00324F>
- [143] A. Ali, A. Memon, J. Yang, J. Akhtar, K. Thebo, (2024) MXene-based Separation Membranes for Water Purification and Desalination. <https://doi.org/10.1039/9781837671663-00049>
- [144] A. Keneshbekova, G. Smagulova, B. Kaidar, A. Imash, A. Ilyanov, R. Kazhdanbekov, E. Yensep, A. Lesbayev, MXene/Carbon Nanocomposites for Water Treatment. *Membranes*, 14(9), (2024) 184. <https://doi.org/10.3390/membranes14090184>
- [145] T. Rasheed, D.B. Ferry, Z.F. Iqbal, M. Imran, M. Usman, Cutting-edge developments in MXene-Derived Functional Hybrid Nanostructures: A Promising Frontier for Next-Generation Water Purification Membranes. *Chemosphere*, 357(2), (2024) 141955. <https://doi.org/10.1016/j.chemosphere.2024.141955>
- [146] K. Huang, C. Li, X. Zhang, L. Wang, W. Wang, X. Meng, Self-Assembly Synthesis of Phosphorus-Doped Tubular $\text{g-C}_3\text{N}_4/\text{Ti}_3\text{C}_2$ MXene Schottky Junction for Boosting Photocatalytic Hydrogen Evolution. *Green Energy & Environment*, 8(1), (2021) 233–245. <https://doi.org/10.1016/j.gee.2021.03.011>
- [147] P. Kuang, Z. Ni, J. Yu, J. Low, New progress on MXenes-based Nanocomposite Photocatalysts. *Materials Reports Energy*, 2(1), (2022) 100081. <https://doi.org/10.1016/j.matre.2022.100081>
- [148] B. Han, Y. H. Hu, MoS_2 as a Co-Catalyst for Photocatalytic Hydrogen Production from Water. *Energy Science & Engineering*, 4(5), (2016) 285–304. <https://doi.org/10.1002/ese3.128>
- [149] M. M. Tunesi, R. A. Soomro, X. Han, Q. Zhu, Y. Wei, B. Xu, Application of MXenes in Environmental Remediation Technologies. *Nano*

- Convergence, 8(1), (2021) 5.
<https://doi.org/10.1186/s40580-021-00255-w>
- [150] Z. Othman, H. R. Mackey, K. A. Mahmoud, A Critical Overview of MXenes Adsorption Behavior toward Heavy Metals. *Chemosphere*, 295, (2022) 133849.
<https://doi.org/10.1016/j.chemosphere.2022.133849>
- [151] A. Kagalkar, S. Dharaskar, N. Chaudhari, Development of MXene for Removal of Lead (Pb²⁺) ions from Wastewater. *Water Practice & Technology*, 19(3), (2024) 911–936.
<https://doi.org/10.2166/wpt.2024.039>
- [152] C. Daulbayev, A. Nursharip, Z. Tauanov, R. Busquets, A. Baimenov, Mechanisms of Mercury Removal from Water with Highly Efficient MXene and Silver-Modified Polyethyleneimine Cryogel Composite Filters. *Advanced Composites and Hybrid Materials*, 7(5), (2024) 139.
<https://doi.org/10.1007/s42114-024-00945-z>
- [153] M. Akbari, J. Rasouli, K. Rasouli, S. Ghaedi, M. Mohammadi, H. Rajabi, S. Sabbaghi, MXene-based Composite Photocatalysts for Efficient Degradation of Antibiotics in Wastewater. *Scientific reports*, 14(1), (2024) 31498.
<https://doi.org/10.1038/s41598-024-83333-3>
- [154] Q. Tan, Z. Yu, Q. Xiang, N. He, R. Long, J. Wang, Photo-Fenton properties of MIL-88A (Fe)/Ti₃C₂ MXene with tunable active crystal facets: universal for degradation of common pollutants in wastewater. *Process Safety and Environmental Protection*, 179, (2023) 405–420.
<https://doi.org/10.1016/j.psep.2023.09.020>
- [155] S. Iravani, R.S. Varma, MXene-Based Photocatalysts in Degradation of Organic and Pharmaceutical Pollutants. *Molecules*, 27(20), (2022) 6939.
<https://doi.org/10.3390/molecules27206939>
- [156] N. Madima, K.K. Kefeni, S.B. Mishra, A.K. Mishra, TiO₂-modified g-C₃N₄ nanocomposite for photocatalytic degradation of organic dyes in aqueous solution. *Heliyon*, 8(9), (2022) e10683.
<https://doi.org/10.1016/j.heliyon.2022.e10683>
- [157] D.R. Rout, H.M. Jena, A. Kumar, O. Baigenzhenov, A. Hosseini-Bandegharai, Graphene-, GO-, and rGO-supported photocatalysts for degradation of organic pollutants: A comprehensive review. *Environmental Technology & Innovation*, 40, (2025) 104560.
<https://doi.org/10.1016/j.eti.2025.104560>
- [158] C. Jin, J. Kang, Z. Li, M. Wang, Z. Wu, Y. Xie, Enhanced visible light photocatalytic degradation of tetracycline by MoS₂/Ag/g-C₃N₄ Z-scheme composites with peroxymonosulfate. *Applied Surface Science*, 514, (2020) 146076.
<https://doi.org/10.1016/j.apsusc.2020.146076>
- [159] S. Liu, Y. Ge, C. Wang, K. Li, Y. Mei, TiO₂/BP/g-C₃N₄ heterojunction photocatalyst for the enhanced photocatalytic degradation of RhB. *Environmental Science and Pollution Research*, 30(35), (2023) 84452–84461.
<https://doi.org/10.1007/s11356-023-28070-2>
- [160] Y. Song, R. Chen, S. Li, S. Yu, X. Ni, M. Fang, H. Xie, Enhancement of Peroxydisulfate Activation for Complete Degradation of Refractory Tetracycline by 3D Self-Supported MoS₂/MXene Nanocomplex. *Nanomaterials*, 14(9), (2024) 786.
<https://doi.org/10.3390/nano14090786>
- [161] B. Chen, A. Feng, R. Deng, K. Liu, Y. Yu, L. Song, MXene as a Cation-Selective Cathode Material for Asymmetric Capacitive Deionization. *ACS Applied Materials & Interfaces*, 12(12), (2020) 13750–13758.
<https://doi.org/10.1021/acsami.9b19684>
- [162] B.A. Samejo, K. Naseer, S. Samejo, F.A. Janjhi, N. Memon, R. Castro-Munoz, G. Boczkaj, MXene-based Composites for Capacitive Deionization—the Advantages, Progress, and their Role in Desalination—a Review. *Water Resources and Industry*, 31, (2024) 100230.
<https://doi.org/10.1016/j.wri.2023.100230>
- [163] F. Dixit, K. Zimmermann, M. Alamoudi, L. Abkar, B. Barbeau, M. Mohseni, B. Kandasubramanian, K. Smith, Application of MXenes for Air Purification, Gas Separation and Storage: A Review. *Renewable and Sustainable Energy Reviews*, 164, (2022) 112527.
<https://doi.org/10.1016/j.rser.2022.112527>
- [164] Z. Cai, M. Hilal, H. Kim, J.H. Kim, C.H. Lee, J. Hou, Two-dimensional Ti₃C₂T_x MXene Integrated with Nickel Oxide for Sensitive NH₃ Sensing at Room Temperature. *Journal of Alloys and Compounds*, 1036, (2025) 181618.
<https://doi.org/10.1016/j.jallcom.2025.181618>
- [165] Guo, C. Feng, Z. Zhang, L. Zhang, C. Xu, C. Zhang, S. Lin, H. Wu, B. Zhang, A. Tabusi, Y. Huang, A Room-Temperature NO₂ Sensor based on Ti₃C₂T_x MXene Modified with Sphere-Like CuO. *Sensors and Actuators B: Chemical*, 375, (2023) 132885.
<https://doi.org/10.1016/j.snb.2022.132885>
- [166] T. He, W. Liu, T. Lv, M. Ma, Z. Liu, A. Vasiliev, X. Li, MXene/SnO₂ heterojunction based Chemical Gas Sensors. *Sensors and Actuators B: Chemical*, 329, (2021) 129275.
<https://doi.org/10.1016/j.snb.2020.129275>

- [167] K. Velusamy, P.V. Chellam, P.S. Kumar, J. Venkatachalam, S. Periyasamy, R. Saravanan, Functionalization of MXene-based Nanomaterials for the Treatment of Micropollutants in Aquatic System: A Review. *Environmental Pollution*, 301, (2022) 119034. <https://doi.org/10.1016/j.envpol.2022.119034>
- [168] D. Bury, M. Jakubczak, R. Kumar, D. Sciezynska, J. Bogacki, P. Marcinowski, A.M. Jastrzębska, Cleaning the environment with MXenes. *MRS Bulletin*, 48(3), (2023) 271-282. <https://doi.org/10.1557/s43577-023-00507-6>
- [169] W.Y. Chen, X. Jiang, S.N. Lai, D. Peroulis, L. Stanciu, Nanohybrids of a MXene and Transition Metal Dichalcogenide for Selective Detection of Volatile Organic Compounds. *Nature Communications*, 11(1), (2020) 1302. <https://doi.org/10.1038/s41467-020-15092-4>
- [170] S. Bagheri, R. Chilcott, S. Luo, A. Sinitskii, Bifunctional Amine- and Thiol-Modified $Ti_3C_2T_x$ MXene for Trace Detection of Heavy Metals. *Langmuir*, 38(42), (2022) 12924–12934. <https://doi.org/10.1021/acs.langmuir.2c02058>
- [171] M.S. Parasnis, Y. Fu, E. Deng, A. Butler, C.T. Chen, R. Dias, H. Lin, F. Yao, P.C. Nalam, High-Performance $Ti_3C_2T_x$ -MXene/Mycelium Hybrid Membrane for Efficient Lead Remediation: Design and Mechanistic Insights. *ACS Applied Materials & Interfaces*, 17(5), (2025) 7838-7848. <https://doi.org/10.1021/acsami.4c19943>
- [172] G. Murtaza, N.E. Hassan, M. Usman, G. Deng, Z. Ahmed, J. Iqbal, M.S. Elshikh, H. Rizwana, R. Iqbal, Effect of MXenes, nZVI and Acacia-Wood Biochar Treatments on Bioavailability Pb and Fractions in Calcareous-Polluted Soils. *Water, Air, & Soil Pollution*, 236(8), (2025) 496. <https://doi.org/10.1007/s11270-025-08146-0>
- [173] A.M. Amani, A. Rahbar, E. Vafa, L. Tayebi, M. Abbasi, H. Kamyab, S. Chelliapan, S.R. Kasaee, A. Vaez, S. Mosleh-Shirazi, Exploring the Functionality of MXenes as Promising Versatile Antimicrobial Agents and their Novel Applications. *Materials Today Communications*, 41, (2024) 110774. <https://doi.org/10.1016/j.mtcomm.2024.110774>
- [174] W. Ye, W. Lao, L. Wu, D.X. Guan, C. Zhang, Y. Feng, L. Mao, Enzyme-Driven Biodegradation of Ti_3C_2 MXene: Unveiling Peroxidase-Mediated Pathways and Enhanced Bioaccumulation Risks in Aquatic Systems. *Environmental Science: Nano*, 12(6), (2025) 3357-3369. <https://doi.org/10.1039/D5EN00124B>
- [175] A.M. Amani, M. Abbasi, A. Najdian, F. Mohamadpour, S.R. Kasaee, H. Kamyab, S. Chelliapan, H. Ardeshiri, L. Tayebi, E. Vafa, S. Mosleh-Shirazi, A Potentially Fruitful Path toward a Cleaner and Safer Environment: MXenes uses in Environmental Remediation. *Ecotoxicology and Environmental Safety*, 297, (2025) 118222. <https://doi.org/10.1016/j.ecoenv.2025.118222>
- [176] M. Alyasi, S. Wahib, T.A. Gomez, K. Rasool, K.A. Mahmoud, The Power of MXene-based Materials for Emerging Contaminant Removal from Water- a Review. *Desalination*, 586, (2024) 117913. <https://doi.org/10.1016/j.desal.2024.117913>
- [177] M. Golgoli, M. Najafi, J. Farahbakhsh, M. Khiadani, M.L. Johns, M. Zargar, Microplastics-resistant FO Membranes: Zwitterionic MOF Nanoparticles for Superior Fouling Control. *Journal of Environmental Chemical Engineering*, 13(2), (2025) 115668. <https://doi.org/10.1016/j.jece.2025.115668>
- [178] W. An, R. Xue, P. Yuan, L. Gao, Q. Xu, D. Hu, J. Ma, Design Strategies of MXene-based Coatings towards Multifunctional Application. *Surfaces and Interfaces*, 46, (2024) 104083. <https://doi.org/10.1016/j.surfin.2024.104083>
- [179] R.G. Ashfaq, M. Arshad, S. Siddique, A. Abrar, S.A. Shah, F. Bulut, S. Altin, Challenges and Recent Advancements in MXene-based High-Capacity Electrodes for Future Generation Rechargeable Batteries. *Journal of Energy Storage*, 132, (2025) 117654. <https://doi.org/10.1016/j.est.2025.117654>
- [180] H. Hu, S. Wang, Y. Zhang, X. Wang, B. Lin, S. Zhang, W. Zhang, P. Lian, MXene-Based Electromagnetic Interference Shielding Materials: A Leap from Fundamental Research to Intelligent Customization. *Small*, 22(13), (2026) 2505417. <https://doi.org/10.1002/sml.202505417>
- [181] H. Ma, C. Li, Y. Yang, Z. Fan, 3D porous MXene Films for Advanced Electromagnetic Interference Shielding and capacitive storage. *Crystals*, 12(6), (2022) 780. <https://doi.org/10.3390/cryst12060780>
- [182] Y.J. Wan, X. M. Li, P. L. Zhu, R. Sun, C.P. Wong, W.H. Liao, Lightweight, Flexible Mxene/Polymer Film with Simultaneously Excellent Mechanical Property and High-Performance Electromagnetic Interference Shielding. *Composites Part A: Applied Science and Manufacturing*, 130, (2020) 105764. <https://doi.org/10.1016/j.compositesa.2020.105764>
- [183] J. Cho, J. Kim, Highly Thermally Conductive and EMI Shielding Composite Fabricated via Free-Radical Polymerization of Poly Acrylic Acid Assisted by expanded Graphite with Liquid Metal-Grafted MXene. *Polymer Composites*, 45(9),

- (2024) 7709–7718. <https://doi.org/10.1002/pc.28298>
- [184] X. Wang, J. Wang, J. Qin, X. Xie, R. Yang, M. Cao, Surface Charge Engineering for Covalently Assembling Three-Dimensional MXene Network for All-Climate Sodium Ion Batteries. *ACS applied materials & interfaces*, 12(35), (2020) 39181–39194. <https://doi.org/10.1021/acsami.0c10605>
- [185] X. Wang, Z. Lei, X. Ma, G. He, T. Xu, J. Tan, L. Wang, X. Zhang, L. Qu, X. Zhang, A lightweight MXene-Coated Nonwoven Fabric with Excellent Flame Retardancy, EMI shielding, and Electrothermal/Photothermal Conversion for Wearable Heater. *Chemical Engineering Journal*, 430(1), (2022) 132605. <https://doi.org/10.1016/j.cej.2021.132605>
- [186] Y. Liu, Y. Wang, N. Wu, M. Han, W. Liu, J. Liu, Z. Zeng, Diverse Structural Design Strategies of MXene-based Macrostructure for High-Performance Electromagnetic Interference Shielding. *Nano-micro letters*, 15(1), (2023) 240. <https://doi.org/10.1007/s40820-023-01203-5>
- [187] K. Qian, Q. Zhou, H. Wu, J. Fang, M. Miao, Y. Yang, S. Cao, L. Shi, X. Feng, Carbonized Cellulose Microsphere@ Void@ Mxene Composite Films with Egg-Box Structure for Electromagnetic Interference Shielding. *Composites Part A: Applied Science and Manufacturing*, 141, (2021) 106229. <https://doi.org/10.1016/j.compositesa.2020.106229>
- [188] P. He, Q. Zhou, Y. Li, Q. Liu, F. Tao, M. Cao, 3D MXene Architectures for Electromagnetic Protection. *Carbon*, 229, (2024) 119564. <https://doi.org/10.1016/j.carbon.2024.119564>
- [189] S. Bin Choi, J.S. Meena, J. Joo, J.W. Kim, Autonomous Self-Healing Wearable Flexible Heaters Enabled by Innovative MXene/Polycaprolactone Composite Fibrous Networks and Silver Nanowires. *Advanced Composites and Hybrid Materials*, 6(227), (2023) 227. <https://doi.org/10.1007/s42114-023-00809-y>
- [190] W. Wang, T. Cai, Z. Cheng, Y. Yang, J. Wang, J. Tang, L. Tang, W. Feng, Y. Liu, Z. Fan, A Shape Programmable Mxene-based Supermolecular Nanocomposite film. *Composites Part A: Applied Science and Manufacturing*, 159, (2022) 106997. <https://doi.org/10.1016/j.compositesa.2022.106997>
- [191] Z. Zhao, M. Murad, C. Pei, H. S. Park, X. Yu, Rational Design of Heterostructured MXene-Based Nanomaterials in Electrocatalytic Water Splitting. *ChemCatChem*, 17(1), (2025). <https://doi.org/10.1002/cctc.202401261>
- [192] H. Liu, Z. Hu, Q. Liu, P. Sun, Y. Wang, S. Chou, Z. Hu, Z. Zhang, Single-atom Ru Anchored in Nitrogen-Doped MXene ($\text{Ti}_3\text{C}_2\text{T}_x$) as An Efficient Catalyst for the Hydrogen Evolution Reaction at all pH Values. *Journal of Materials Chemistry A*, 8(46), (2020) 24710–24717. <https://doi.org/10.1039/d0ta09538a>
- [193] X. Zhao, X. Zheng, Q. Lu, Y. Li, F. Xiao, B. Tang, S. Wang, D.Y.W. Yu, A.L. Rogach, Electrocatalytic enhancement Mechanism of Cobalt Single Atoms Anchored on different MXene Substrates in Oxygen and Hydrogen evolution reactions. *EcoMat*, 5(2), (2022). <https://doi.org/10.1002/eom2.12293>
- [194] X. Sun, J. Wang, J. Yu, Y. Jing, J. Liu, M. Singh, P.D. Lund, M.I. Asghar, Self-Assembled Formation of Platinum Single Atoms and Nanoclusters Stabilized on MXene as an Efficient Catalyst for Boosting Electrocatalytic hydrogen evolution. *International Journal of Hydrogen Energy*, 84, (2024) 502–510. <https://doi.org/10.1016/j.ijhydene.2024.08.263>
- [195] Z. Meng, B. Zhang, Q. Peng, Y. Yu, J. Zhou, Z. Sun, Mxenes Modified by Single Transition Metal Atom for Hydrogen evolution reaction catalysts. *Applied Surface Science*, 562, (2021) 150151. <https://doi.org/10.1016/j.apsusc.2021.150151>
- [196] X. Wang, J. Ding, W. Song, X. Yang, T. Zhang, Z. Huang, H. Wang, X. Han, W. Hu, Cation Vacancy Clusters in $\text{Ti}_3\text{C}_2\text{T}_x$ MXene Induce Ultra-Strong Interaction with Noble Metal Clusters for Efficient Electrocatalytic Hydrogen Evolution. *Advanced Energy Materials*, 13(23), (2023). <https://doi.org/10.1002/aenm.202300148>
- [197] S. Ranjith, S. M. Ghoreishian, R. Umapathi, G. S. R. Raju, H. U. Lee, Y. S. Huh, Y. Han, WS_2 -intercalated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/ TiO_2 -stacked Hybrid Structure as an Excellent Sonophotocatalyst for Tetracycline Degradation and Nitrogen Fixation. *Ultrasonics Sonochemistry*, 100, (2023) 106623. <https://doi.org/10.1016/j.ultsonch.2023.106623>
- [198] Y. Lv, J. He, Y. Yang, M. Huang, D. He, Y. Wang, Facile Synthesis of $\text{MnO}_2@\text{Ti}_3\text{C}_2\text{T}_x$ Composite Electrodes for superior performance supercapacitor. *Journal of Solid State Chemistry*, 344, (2025) 125198. <https://doi.org/10.1016/j.jssc.2025.125198>
- [199] Y. Zhu, Y. Ma, D. Wu, G. Jiang, Preparation and Gas Sensing Properties of ZnO/MXene Composite Nanomaterials. *Sensors and Actuators A Physical*, 344, (2022) 113740. <https://doi.org/10.1016/j.sna.2022.113740>
- [200] J. Wang, X. Wei, X. Wang, W. Song, W. Zhong, M. Wang, J. Ju, Y. Tang, Plasmonic Au Nanoparticle@ $\text{Ti}_3\text{C}_2\text{T}_x$ Heterostructures for

- Improved Oxygen Evolution Performance. *Inorganic Chemistry*, 60(8), (2021) 5890–5897. <https://doi.org/10.1021/acs.inorgchem.1c00302>
- [201] P. Jin, P. Han, X. Li, K. Li, Titanium Carbide MXenes-Initiated Plasmonic Metal-Support Interaction for effective Photocatalysis on Uncoated Ag Nanoparticles. *Applied Surface Science*, 612, (2022) 155850. <https://doi.org/10.1016/j.apsusc.2022.155850>
- [202] L. Li, T. Zhang, L. Zhang, G. Wang, X. Huang, W. Li, L. Wang, Y. Li, J. Li, R. Lu, Synergistic enhancement of Chemical and Electromagnetic Effects in a $\text{Ti}_3\text{C}_2\text{T}_x/\text{AgNPs}$ Two-Dimensional SERS Substrate for ultra-sensitive detection. *Analytica Chimica Acta*, 1331, (2024) 343330. <https://doi.org/10.1016/j.aca.2024.343330>
- [203] A. Asghar, M. S. Rashid, M. Hanif, I. Boukhris, Z. Chen, M. Saqib, Q. Arshad, P. Rosaiah, S. Ali, I. Hussain, Advancements in MXene-based 3D Printing-based Technologies. *Chemical Engineering Journal*, 506, (2025) 159811. <https://doi.org/10.1016/j.cej.2025.159811>
- [204] Y. Zhang, J. Yu, J. Lu, C. Zhu, D. Qi, Facile construction of 2D MXene ($\text{Ti}_3\text{C}_2\text{T}_x$) based Aerogels with Effective Fire-Resistance and Electromagnetic Interference Shielding Performance. *Journal of Alloys and Compounds*, 870, (2021) 159442. <https://doi.org/10.1016/j.jallcom.2021.159442>
- [205] Y. Chen, T. Zuo, Y. Jiang, J. Gui, W. Feng, D. Yu, W. Wang, Lightweight, Robust and Conductive MXene/ SiO_2 Nanofiber Aerogels for Excellent Sensing and Thermal Management Properties. *Composites Part B: Engineering*, 283, (2024) 111669. <https://doi.org/10.1016/J.COMPOSITESB.2024.111669>
- [206] T. Lv, J. Zhang, L. Yu, Y. Zhao, T. Zhao, Y. Yang, C. Yu, C. Zhao, G. Xing, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene/Loofah-Derived Carbon Aerogel for High-Efficiency Adsorption of Organic Pollutants in Wastewater. *Journal of Industrial and Engineering Chemistry*, 144, (2024) 454–462. <https://doi.org/10.1016/j.jiec.2024.09.040>
- [207] L. Zheng, Y. Yang, H. Zhang, T. Liao, Y. Han, M. Yu, MXene-Assisted Construction of Versatile Cellulose-based Aerogels with Multilayered Structure for Piezoresistive Sensing and Contaminant Adsorption. *International Journal of Biological Macromolecules*, 308(Part 1), (2025) 142382. <https://doi.org/10.1016/j.ijbiomac.2025.142382>
- [208] D. Zhang, J. Jiang, Y. Yang, F. Li, H. Yu, X. Dong, T. Wang, T. Wang, SnO_2 -inserted 2D Layered $\text{Ti}_3\text{C}_2\text{T}_x$ MXene: From Heterostructure Construction to Ultra-High Sensitivity for Ppb-level H_2S Detection. *Sensors and Actuators B Chemical*, 410, (2024) 135727. <https://doi.org/10.1016/j.snb.2024.135727>
- [209] A. Alam, G. Saeed, K. woo Kim, J.K. Kim, H.S. Park, S. Lim, Direct Ink Writing (DIW) printed high-performance asymmetric supercapacitor based on 0D@2D silver-nanoparticles@MXene as anode and 0D@2D MnO_2 -nanoparticles@MXene as cathode materials. *Journal of Energy Storage*, 72 Part B, (2023) 108227. <https://doi.org/10.1016/j.est.2023.108227>
- [210] J. Song, W. Shang, W. Zhou, J. Li, X. Wu, W. Li, R. Zhang, S. Liu, from issues to solutions: 3D printing for overcoming challenges in liquid- and solid-state batteries. *Energy Storage Materials*, 79, (2025) 104342. <https://doi.org/10.1016/j.ensm.2025.104342>
- [211] Y. Wang, F. Wang, C. Shi, H. Dong, Y. Song, J. Zhao, Z. Ling, Monolithic MXene aerogels encapsulated phase change composites with superior photothermal conversion and storage capability. *Nanomaterials*, 13(10), (2023)1661. <https://doi.org/10.3390/nano13101661>
- [212] B. Peng, Y. Gao, Q. Lyu, Z. Xie, M. Li, L. Zhang, J. Zhu, Cationic photothermal hydrogels with bacteria-inhibiting capability for freshwater production via solar-driven steam generation. *ACS applied materials & interfaces*, 13(31), (2021) 37724–37733. <https://doi.org/10.1021/acsami.1c10854>
- [213] J. Orangi, H. Tetik, P. Parandoush, E. Kayali, D. Lin, M. Beidaghi, Conductive and Highly Compressible MXene Aerogels with Ordered Microstructures as High-Capacity Electrodes for Li-ion capacitors. *Materials Today Advances*, 9, (2021) 100135. <https://doi.org/10.1016/j.mtadv.2021.100135>
- [214] J. Wei, S. Jia, C. Ma, J. Guan, C. Yan, L. Zhao, Z. Shao, Nacre-Inspired Composite Film with Mechanical Robustness for Highly Efficient Actuator Powered by Humidity Gradients. *Chemical Engineering Journal*, 451, (2022) 138565. <https://doi.org/10.1016/j.cej.2022.138565>
- [215] Y.H. Auh, N.N. Neal, K. Arole, N.A. Regis, T. Nguyen, S. Ogawa, Y. Tsuda, A. Yoshigoe, M. Radovic, M.J. Green, H. Yamaguchi, J.L. Lutkenhaus, Nacre-like MXene/Polyacrylic acid Layer-by-Layer Multilayers as hydrogen gas barriers. *ACS Applied Materials & Interfaces*, 17(21), (2025) 31392–31402. <https://doi.org/10.1021/acsami.5c03632>

- [216] C. He, L. Yu, Y. Jiang, L. Xie, X. Mai, P. Ai, B. Xue, Deep-Learning Approach for Developing Bilayered Electromagnetic Interference Shielding Composite Aerogels based on Multimodal Data Fusion Neural Networks. *Journal of Colloid and Interface Science*, 688, (2025) 79–92. <https://doi.org/10.1016/j.jcis.2025.02.133>
- [217] M. Yu, X. Feng, Scalable Manufacturing of MXene Films: Moving toward Industrialization. *Matter*, 3(2), (2020) 335–336. <https://doi.org/10.1016/j.matt.2020.07.011>
- [218] M. Shekhirev, C. E. Shuck, A. Sarycheva, Y. Gogotsi, Characterization of MXenes at Every Step, from their Precursors to Single Flakes and Assembled Films. *Progress in Materials Science*, 120, (2020) 100757. <https://doi.org/10.1016/j.pmatsci.2020.100757>
- [219] Y.Z. Chu, M. Hoover, P. Ward, K.C. Lau, First-Principles Study of Mxene Properties with Varying Hydrofluoric Acid concentration. *iScience*, 27(2), (2024) 108784. <https://doi.org/10.1016/j.isci.2024.108784>
- [220] C.W. Wu, B. Unnikrishnan, I.W.P. Chen, S.G. Harroun, H.T. Chang, C.C. Huang, Excellent oxidation resistive MXene aqueous ink for micro-supercapacitor application. *Energy Storage Mater*, 25, (2020) 563–571. <https://doi.org/10.1016/j.ensm.2019.09.026>
- [221] M.D. Firouzjaei, S.K. Nemani, M. Sadrzadeh, E.K. Wujcik, M. Elliott, B. Anasori, Life-Cycle Assessment of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene synthesis. *Advanced Materials*, 35(31), (2023) e2300422. <https://doi.org/10.1002/adma.202300422>
- [222] N. Anjum, O. A. Ekuase, V. O. Eze, O. I. Okoli, Ti-based MXENEs for Energy Storage Applications: Structure, Properties, Processing Parameters and Stability. *ECS Journal of Solid State Science and Technology*, 11(9), (2022) 093008. <https://doi.org/10.1149/2162-8777/ac9336>
- [223] C. Shi, X. Zhang, Z. Li, T.T. Beyene, T. Zheng, Y. Liu, K. Zhu, Review and perspectives on preparation strategies and applications of Ti_3C_2 MXene for Li metal batteries/Li–S batteries. *Energy & Fuels*, 38(16), (2024) 14866–14890. <https://doi.org/10.1021/acs.energyfuels.4c02106>
- [224] W. Sun, S.A. Shah, Y. Chen, Z. Tan, H. Gao, T. Habib, M. Radovic, M.J. Green, Electrochemical Etching of Ti_2AlC to Ti_2CT_x (MXene) in Low-Concentration Hydrochloric Acid Solution. *Journal of Materials Chemistry A*, 5(41), (2017) 21663–21668. <https://doi.org/10.1039/c7ta05574a>
- [225] Z. Xiao, X. Xiao, L. B. Kong, H. Dong, X. Li, X. Sun, B. He, S. Ruan, J. Zhai, MXenes and MXene-based composites for Energy Conversion and Storage Applications. *Journal of Materiomics*, 9(6), (2023) 1067–1112. <https://doi.org/10.1016/j.jmat.2023.04.013>
- [226] X. Li, M. Zhan, Y. Liu, W. Tu, H. Li, MXENE Synthesis and Carbon Capture Applications: Mini-Review. *Chemistry - A European Journal*, 30(49), (2024) e202400874. <https://doi.org/10.1002/chem.202400874>
- [227] W. Wu, H. Ge, L. Zhang, X. Lei, Y. Yang, Y. Fu, H. Feng, Evaluating the Cytotoxicity of Ti_3C_2 MXene to Neural Stem cells. *Chemical Research in Toxicology*, 33(12), (2020) 2953–2962. <https://doi.org/10.1021/acs.chemrestox.0c00232>
- [228] K. Diedkova, I. Roslyk, N. Kanas, L. Grine, V. Deineka, A. Blacha-Grzechnik, M. Boroduskis, I. Iatsunskyi, B. Anastaziak, A. Konieva, P. Shubin, W. Simka, M. Truhins, O. Sulaieva, I. Yanko, V. Zahorodna, G. Stojanovic, O. Gogotsi, Y. Gogotsi, M. Pogorielov, Effects of etching and delamination on biocompatibility of Ti-based MXenes. *ACS applied materials & interfaces*, 17(34), (2025) 47919–47937. <https://doi.org/10.1021/acsami.5c08807>
- [229] Y. Gogotsi, (2023). MXenes: From discovery to applications of two-dimensional metal carbides and nitrides, CRC Press. <https://doi.org/10.1201/9781003306511>
- [230] S. Guha, A. Kabiraj, S. Mahapatra, High-Throughput Design of Functional-Engineered Mxene Transistors with low-Resistive Contacts. *Npj Computational Materials*, 8(1), (2022). <https://doi.org/10.1038/s41524-022-00885-6>
- [231] Jiang, H. Liu, H. He, S. Li, Y. Hou, K. Wu, Y. Cheng, B. Xiao, Twisted Bilayer MXenes// MoS_2 Moiré Superlattices for Alkaline Metal-Ion Batteries: Insights from First-Principles Calculations. *The Journal of Physical Chemistry C*, 129(13), (2025) 6109–6128. <https://doi.org/10.1021/acs.jpcc.5c00326>
- [232] M. M. Muhammed, J. H. Mokkath, Observation of Robust Infrared Plasmons in Twisted Titanium Carbide (Ti_3C_2) MXene. *Journal of Physics and Chemistry of Solids*, 164, (2022) 110612. <https://doi.org/10.1016/j.jpcs.2022.110612>
- [233] H. Wang, R. Zhao, H. Hu, X. Fan, D. Zhang, D. Wang, 0D/2D Heterojunctions of Ti_3C_2 MXene QDs/SiC as an Efficient and Robust Photocatalyst for Boosting the Visible Photocatalytic NO Pollutant Removal Ability. *ACS Applied Materials & Interfaces*, 12(36), (2020) 40176–40185. <https://doi.org/10.1021/acsami.0c01013>

- [234] W. Luo, H. Liu, X. Liu, L. Liu, W. Zhao, Biocompatibility Nanoprobe of MXene N-Ti₃C₂ Quantum dot/Fe³⁺ for Detection and Fluorescence Imaging of Glutathione in Living Cells. *Colloids and Surfaces B Biointerfaces*, 201, (2021) 111631. <https://doi.org/10.1016/j.colsurfb.2021.111631>
- [235] B. Lu, Y. Xia, Y. Ren, M. Xie, L. Zhou, G. Vinai, S.A. Morton, A.T.S. Wee, W.G. Van Der Wiel, W. Zhang, P.K.J. Wong, When Machine Learning Meets 2D Materials: A review. *Advanced Science*, 11(13), (2024) e2305277. <https://doi.org/10.1002/advs.202305277>
- [236] P. Awasthi, B. Maharjan, S. Shrestha, D.P. Bhattarai, D. Yoon, C.H. Park, C.S. Kim, Synthesis, Characterizations, and Biocompatibility Evaluation of Polycaprolactone–MXene Electrospun Fibers. *Colloids and Surfaces A Physicochemical and Engineering Aspects*, 586, (2019) 124282. <https://doi.org/10.1016/j.colsurfa.2019.124282>
- [237] Y. Hu, Y. Wei, M. Liao, S. Han, X. Gao, X. Gao, Y. Wang, S. Zhou, D. Xu, X. Zhuang, Y. Yang, H. Cheng, B. Zhang, Q. Cui, J. Qi, L. Tian, W. Li, X. Gao, X. Gao, R. Chai, Cochlear Implant/MXene-based Electroacoustic Stimulation Modulates the Growth and Maturation of Spiral Ganglion Neurons. *Engineered Regeneration*, 5(4), (2024) 443–451. <https://doi.org/10.1016/j.engreg.2024.10.001>
- [238] M. Mirzayi, B. Khalilzadeh, S.A. Nakhjavani, R. Mohammad-Rezaei, Highly Efficient Assessment and Selective Determination of Pancreatic Cancer Biomarker CA-19-9 using Co-Electrodeposited MXene-AgNPs Nanocomposite. *Sensing and Bio-Sensing Research*, 47, (2025) 100753. <https://doi.org/10.1016/j.sbsr.2025.100753>

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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Authors Contribution Statement

Arun Kumar Senthil Kumar: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Methodology, Data curation, Formal analysis. Ayesha Kousar: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Methodology, Data curation, Formal analysis. Jih-Hsing Chang: Supervision, Writing - Review & Editing, Validation. A. Kalaivani: Writing - Review & Editing. Mohanraj Kumar: Supervision, Conceptualization, Methodology, Writing - Review & Editing, Validation. All the authors read and approved the final version of the manuscript.

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