

Review

Functionalized MXenes for Enhanced Visible-Light Photocatalysis: A Focus on Surface Termination Engineering and Composite Design

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Abstract: MXenes, a groundbreaking class of two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides, have emerged as highly promising materials for photocatalytic applications due to their unique structural, electrical, and surface properties. These materials are synthesized by selectively etching the A layer from MAX phases, yielding compositions with the general formula $M_{n+1}X_nT_x$, where M is a transition metal, X represents carbon or nitrogen, and T_x refers to surface terminations such as ^-OH , ^-O , or ^-F . This review delves into the advanced synthesis techniques of MXenes, including fluoride-free etching and molten salt methods, and explores their potential in photocatalysis for environmental remediation. MXenes exhibit remarkable light absorption capabilities and efficient charge carrier separation, making them highly effective for the photocatalytic degradation of organic pollutants under visible light. Modulating their surface chemistry and bandgap via functional group modifications further enhances their photocatalytic performance. These attributes position MXenes as next-generation materials for sustainable photocatalytic applications, offering significant potential in addressing global environmental challenges.

Keywords: photocatalysis; MXenes; pollutants; environmental remediation



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1. Introduction

Layers of firmly bound atoms are kept together by weak interlayer van der Waals forces in 2D materials [1]. Two-dimensional materials' unusual physical, chemical, and electrical features, such as a high surface-to-volume ratio, intrinsic flexibility, and customizable surface properties, have drawn study interest [2]. These features make 2D materials suitable for energy storage, photonic devices, and sensing [3].

In 2011, Naguib et al. created MXenes, transition metal carbides, nitrides, or carbonitrides, a developing class of 2D materials. MXenes are synthesized by selectively etching layer A from layered ternary carbides and nitrides (MAX phase) precursors, which are layered materials formulated as $M_{n+1}AX_n$, where M is an early transition metal (e.g., Sc, Ti, V, Cr, Zr, Nb, Mo, Hf, Ta), A is an element from group 13 or 14 of the periodic table, and X is carbon or nitrogen [4,5]. MXenes have the generic formula $M_{n+1}X_nT_x$, where n is an integer from 1 to 3, and T represents surface functional groups (^-OH , ^-O , and ^-F). Alkalization or calcination may remove surface functional groups, depending on the application [6].

Photocatalytic degradation, which converts solar energy into chemical energy, is an effective strategy for environmental remediation and sustainable energy use, resulting in

the degradation of pollutants without secondary pollution [7–9]. Research on MXenes reveals significant success in different environmental uses, including water cleanup techniques with complementary capabilities for energy storage and environmental detection systems [10]. Their large surface area, high conductivity, and broad substance interaction qualities make MXenes exceptionally versatile for environmental cleanup and sustainable technology research. The research overview now appears in the introductory section [11]. The worldwide photocatalyst market was worth USD 1.65 billion in 2016 and will steadily increase its immense property [12]. Photocatalytic degradation involves light absorption and the photoexcitation of e^- - h^+ couples when photon energy surpasses the bandgap (λ_g (nm) = $1240/E_g$ (eV)); then, energized e^- and h^+ travel to the surface and react with absorbed electron donors/acceptors to form active species [13,14]. Finally, redox interactions between active species and pollutants destroy the pollutants [15,16]. Due to inefficient sunlight harvesting, photogeneration, charge separation, transfer, and photocatalytic reactions, most single catalysts cannot meet practical application requirements [17]. Wide-bandgap semiconductors like TiO_2 only respond to UV light and use just <5% of sunshine [18]. The photocatalytic process frequently involves excited-state electron and hole recombination in the conduction and valence bands, dissipating energy as heat. For this reason, cocatalysts are commonly used to promote photogenerated electron and hole transport and separation [19]. Commercially, natural resource scarcity and exorbitant costs are the biggest concerns. MXenes, two-dimensional transition metal carbides and nitrides, have high electrical conductivity and light-trapping efficiency, making them promising photocatalytic degradation materials [20].

MXenes, a recently discovered class of two-dimensional transition metal carbides, nitrides, and carbonitrides, represent a significant breakthrough in nanomaterials due to their unique electrical, mechanical, and chemical properties. Unlike traditional 2D materials, MXenes offer a high surface area, tunable surface chemistry, and exceptional conductivity, making them highly effective for environmental and biomedical applications. This review provides novel insights into the advanced synthesis methods of MXenes, including fluoride-free and selective etching techniques. It also highlights the unprecedented potential of MXenes in photocatalysis applications, where they demonstrate superior pollutant degradation compared to conventional materials. These innovations position MXenes as a transformative material for future technologies.

2. Structure of MXenes

The top-down synthesis of MXenes involves the selective removal of certain atoms from the structure of MAX phases, such as Al, Si, and Ga. Layered ternary carbides and nitrides with a hexagonal structure are known as MAX phases. Loosely stacked MX layers, or “MXenes” as they are called because of their two-dimensionality, are formed due to this procedure. Separating these MX layers into individual flakes is also possible [20,21]. The exfoliation of the A phase from the MAX phase forms MXenes, which have an accordion-like shape due to the expansion of their basal planes. Like their parent MAX predecessors, MXenes have hexagonal symmetry and a $P6_3/mmc$ space group [20]. The parent structure has a close-packed arrangement of transition metal (M) atoms and octahedral interstitial gaps occupied by X-element atoms. Given the close correlation between the transition metals and the surface terminations, as shown by the significantly negative formation energy of MXenes, these materials are anticipated to be fully terminated. While titanium (Ti), carbon (C), oxygen (O), and fluorine (F) were found in the investigation by Naguib et al., almost no aluminum (Al) was found. This implies that oxygen was used instead of aluminum. According to TEM analysis, the carbon grid behind the MXene layer was visible because the material was sufficiently thin. Only in terms of Ti’s molecular size did the thin

sheets resemble each other. As previously mentioned [20], the intercalated epitaxial films of MXenes display remarkable transparency, boasting a visible-light transmittance rate of 90%. Despite the exfoliation process, the Ti_3AlC_2 material maintained its pseudo-ductility. M. Khazaei et al. [22] performed computational research showing that an M_2X system has a hexagonal unit cell with three-layer sheets and two M transition layers densely packed around the X (C or N) layer. The A site has no 'X' atoms underneath the transition metals in the MXene layers; the B site contains 'X' atoms. Several types of configurations are determined by where the functional groups are located: (1) above M_3X_3 hollow sites without adjacent X atoms; (2) above M_3X_3 hollow sites with X atoms accessible; and (3) above M_3X_3 hollow sites with X atoms on both sides [23]. Figure 1 depicts atomistic models representing the various architectures of MXenes discovered so far [24].

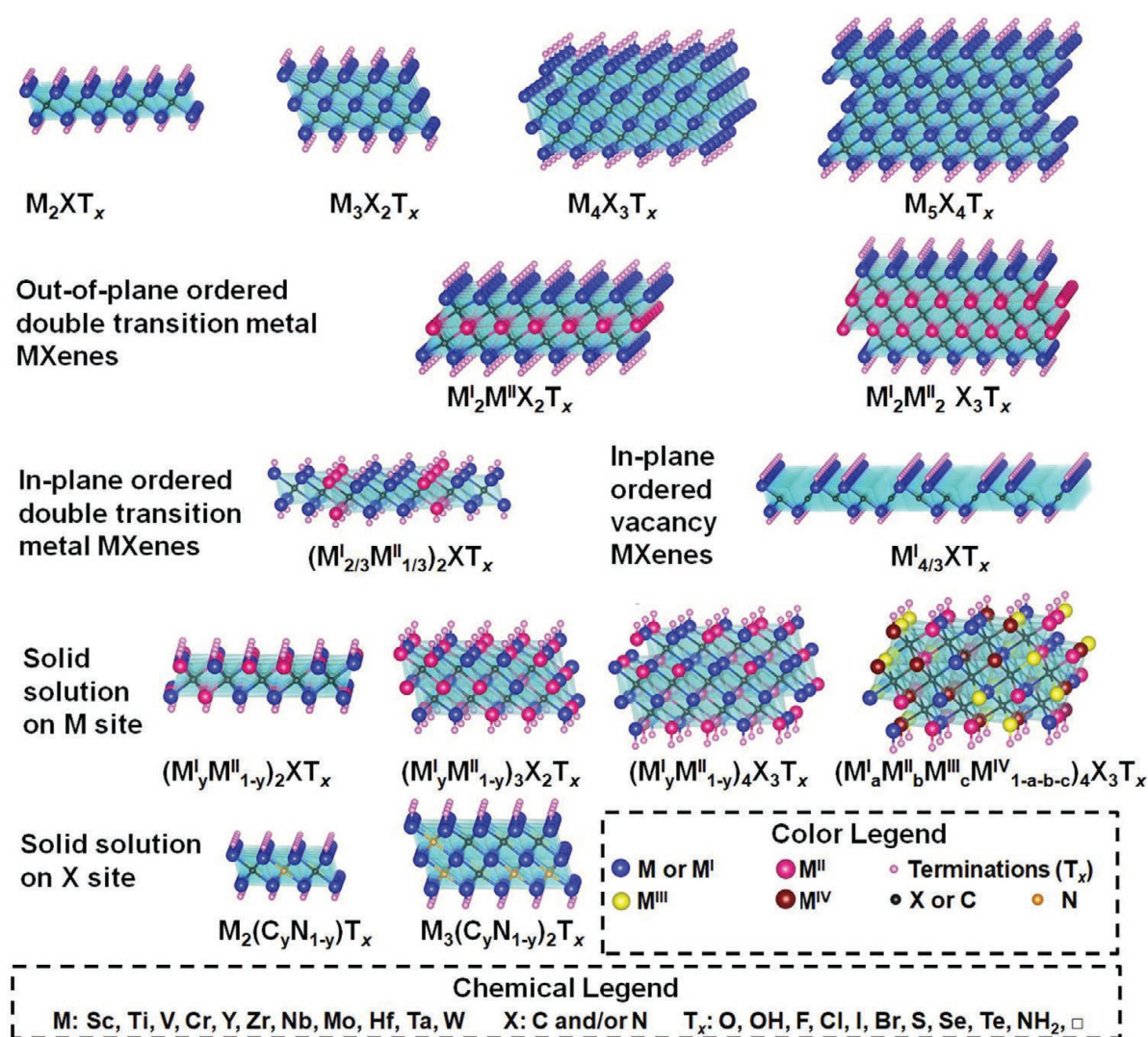


Figure 1. The structures and compositions of typical MXenes. In the formula of MXenes, which is $\text{M}_{n+1}\text{X}_n\text{T}_x$, M is an early transition metal, X is either carbon or nitrogen, and T_x is the symbol for surface terminations. A range of 1–4 is possible for the n value. One, two, or more transition metal atoms may occupy the M sites, leading to solid solutions or organized structures. Ordered double-transition metal MXenes can be found in various structures, including in-plane vacancy structures (i-MXenes) like $\text{Mo}_{2/3}\text{CT}_x$ and $(\text{Mo}_{2/3}\text{Y}_{1/3})_2\text{CT}_x$, and out-of-plane ordered structures (o-MXenes) like $\text{Cr}_2\text{TiC}_2\text{T}_x$ or $\text{Mo}_2\text{Ti}_2\text{C}_3\text{T}_x$, which consist of one or two layers of MII transition metal sandwiched between MI transition metals. Reprinted with permission from [24]. Copyright (2021), John Wiley and Sons.

3. Synthesis and Processing of MXenes

3.1. Selective Etching Method

One typical method for creating MXenes involves selectively deleting layers from parent MAX phases. For this particular method, acidic solutions containing fluoride ions have been widely used as etchants [25]. The by-product is made by mixing stacked MAX phase powders with water-based HF acid and letting them sit at room temperature for a while. Consequently, weak linkages of surface terminations like hydroxyl, fluoride, or oxygen on the ML-MXene surface replace the metallic connections between the MX layers. To maintain a pH between 4 and 6, the mixture is rinsed with deionized water after centrifugation and filtration to separate the liquid from the solid. This process creates MXenes with a minimal amount of FL layers. When there are less than five layers in a MXene, we call it an FL [26]. Note that MXene flakes may become wrinkled as the MXene solution's pH drops, such as when $\text{Ti}_3\text{C}_2\text{T}_x$ reaches a pH of around one [27,28]. In addition, $\text{Mo}_2\text{Ga}_2\text{C}$ may be used as a source of MXenes since it is the first precursor used to create Mo_2CT_x MXenes by removing Ga layers [28]. The presence of two GaA layers sets $\text{Mo}_2\text{Ga}_2\text{C}$ apart from a MAX phase, which only has one. The $\text{Zr}_3\text{C}_2\text{T}_x$ MXene etching procedure eliminates the aluminum (Al) and aluminum carbide (Al_3C_3) layers, an advantage over the conventional etching method. $\text{Zr}_3\text{Al}_3\text{C}_5$ is the building block of this MXene. Creating MXenes by etching the MAX phase at high temperatures is feasible. In 2016, this method was used experimentally to synthesize the first nitride-based MXene. A mixture of molten salts, including 59% potassium fluoride, 29% lithium fluoride, and 12% sodium fluoride, was used to erode the aluminum layer of Ti_4AlN_3 powder under an inert argon gas environment at 550 °C [29]. Tetrabutylammonium hydroxide (TBAOH) was used to exfoliate the powder further, producing the MXenes described in [30]. The targeted removal of atomic layers employing chemical etching procedures following treatment with nitride, carbide, and carbo-nitride agents has created at least 20 MXenes. Two main types of etchants exist: those that use a wide variety of ions and those that use water-based salts, which include fluorine ions [31]. The first steps include breaking the M-A bonds in MAX systems to isolate the MXenes from the rest of the molecule. The duration of corrosion and the amount of liquid agitation are the two variables that determine the effectiveness of such a method.

$\text{Ti}_3\text{C}_2\text{T}_x$'s electrical conductivity, chemical makeup, lateral dimensions, surface terminations, etching efficiency, and defects are all significantly affected by its synthesis techniques. Since its discovery in 2011, the manufacture of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene has been the subject of much research, mainly focusing on the etching technique. Fluoride etching, etching with fluoride-based salts, and etching without fluoride are among the several methods studied to produce $\text{Ti}_3\text{C}_2\text{T}_x$ MXene [32–35]. A mixture of fluoride salts, usually LiF and NH_4HF_2 , is used as the etchant in fluoride-based salt etching. This method integrates etching and fluoride-ion intercalation in a complementary manner. Adding lithium ions to the MXene layers may make them more spaced apart, making it more straightforward for ions to travel between them and the MXenes more resilient to the volume changes that occur during cycling. Increased capacitance and improved energy storage capabilities result from greater pseudocapacitive behavior brought about by more intercalated ions. To avoid using vital fluoride compounds, etchants such as aqueous solutions of acids (e.g., HCl, H_2SO_4) or other chemicals (e.g., LiCl/ AlCl_3 combination) may be used in fluoride-free operations. These processes can produce MXene by-products that differ from fluoride-etched MXenes in surface chemistry and structural characteristics. The material's water-repellent properties, charge-transfer rates, and surface reactivity might be compromised without fluorine termination. Various etchants affect the electrochemical performance of fluoride-free-etched MXenes [36,37]. An initial proposal for a solvent-free,

one-step gas-phase dry etching process was “Gas-Phase Selective Etching.” This approach used the high oxidation capacity of halogen and hydrogen halide gases to etch various A elements (Al, Si, Sn, etc.) from MAX phases, investigated by Zhu et al. [38]. Figure 2a provides a concise overview of the etching process. Heating a gas precursor in a vacuum ampoule causes the etching gas to be released and react with the Al in Ti_3AlC_2 (Figure 2b). Gaseous by-products (such as aluminum halide, for example, AlI_3 / AlBr_3 / AlCl_3) are produced when the etching gas oxidizes Al in the high-temperature zone (Figure 2c). The separation of the MXenes and by-products is accomplished by depositing the by-products with low boiling points in the sub-high-temperature zone, also known as the stationary zone, caused by the temperature differential between the two ends of the ampoule. After the reaction, $\text{Ti}_3\text{C}_2\text{I}_x$ / 2Br_2 / $\text{Ti}_3\text{C}_2\text{Cl}_2$ is created in the high-temperature zone. This allows for the synthesis of MXene ($\text{Ti}_3\text{C}_2\text{Br}_2$ / $\text{Ti}_3\text{C}_2\text{Cl}_2$) powder (Figure 2d) [38].

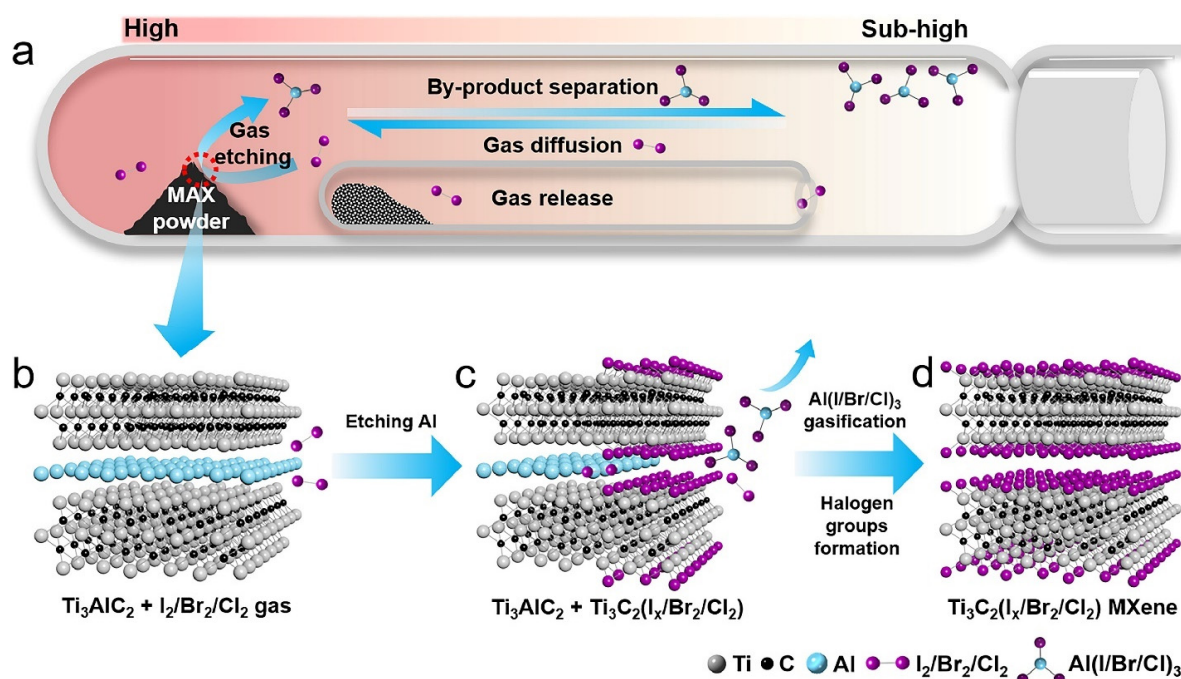
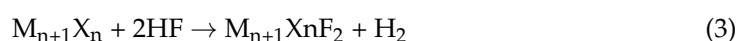
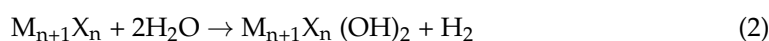
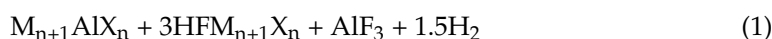


Figure 2. (a–d) A schematic illustrating the gaseous etching process for the fabrication of MXenes. Reprinted/adapted with permission from [38]. Copyright (2024) Elsevier.

3.1.1. HF Etching

The following procedure is often used to produce MXenes [39,40]: etching the A layer of a MAX phase.



The A components are removed from the MAX phase in Reaction (1), creating the M_{n+1}X_n phase. Reactions (2) and (3) produce the functional groups [41]. The panel shows the exfoliation process, whereas Panel B shows the characterization of the structural morphology for Ti_3AlC_2 . After soaking Ti_3AlC_2 particles in a 50% concentrated HF solution for two hours, Naguib et al. created an accordion-like $\text{Ti}_3\text{C}_2\text{T}_x$ MXene [42]. When etching Al from Ti_3AlC_2 in a solution with 50% HF, Mashtalir et al. looked at how particle size and process parameters affected the etching process. Research has shown that lowering

the maximum original particle size, extending the reaction time, and elevating the immersion temperature improves the phase transition from bulky Ti_3AlC_2 to $\text{Ti}_3\text{C}_2\text{T}_x$ [43]. An accordion-like particle shape is typically seen when the HF concentration reaches around 10%. In addition, the quality, environmental stability, and characteristics of the MXene material are negatively impacted by an increase in the number of flaws in the $\text{Ti}_3\text{C}_2\text{T}_x$ flakes caused by a more significant fraction of HF [24,44]. The HF method is ideal for etching aluminum-containing MAX phases and portions of non-MAX phases because of its low reaction temperature and ease of usage. However, HF is a very corrosive and poisonous etchant, which creates operational dangers and harmful environmental effects [45].

Murugesan et al. achieved a high yield of Ti_3C_2 MXene sheets by selectively etching titanium aluminum carbide (Ti_3AlC_2) powder to remove Al atoms. In brief, 1 g of Ti_3AlC_2 powder was combined with 10 milliliters of a 40% concentrated HF solution and then stirred using a magnetic mixer set at 400 revolutions per minute for 24 h at room temperature. To obtain the MXene layer precipitate, the collected material was spun in a centrifuge at 4500 rpm with DDI water and ethanol until the pH reached 6. After that, it was heated in an oven at 60 °C for 8 h. The 2D Ti_3C_2 MXene sheets were finally obtained (Figure 3a) [46].

3.1.2. Fluoride-Based Salt Etching

When the $\text{Ti}_3\text{C}_2\text{T}_x$ flakes are concentrated to around 10%, they tend to take on a particle structure that looks like an accordion. The quality, environmental stability, and MXene properties of the $\text{Ti}_3\text{C}_2\text{T}_x$ flakes may be affected by the increased flaws caused by a higher fraction of HF [47]. Even though HF etching is a user-friendly and effective way to remove certain non-MAX and MAX phases that contain aluminum (thanks to its low reaction temperature), this etchant is highly toxic, corrosive, and can cause operational hazards and adverse environmental effects. According to TEM research, the usual range of sizes for $\text{Ti}_3\text{C}_2\text{T}_x$ flakes is 500 to 1500 nm. The concentration of HCl and LiF used to produce the fluoride-based salt affects the dimensions, computing capabilities, and excellence of $\text{Ti}_3\text{C}_2\text{T}_x$. The $\text{LiF}:\text{Ti}_3\text{AlC}_2$ molar ratios, which range from 5.0 to 7.5, are enhanced, leading to more extensive and better $\text{Ti}_3\text{C}_2\text{T}_x$ flakes when the HCl concentration is increased from 6 mol/L to 9 mol/L [48].

The synthesis of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene has been carried out using several fluoride salts, including NH_4HF_2 , KF, NaF, FeF_3 , NH_4F , and LiF. The ability of NH_4HF_2 to etch epitaxial Ti_3AlC_2 films formed by sputtering at room temperature was revealed in 2014. The c-lattice properties of the films intercalated with NH_3 and NH_4^+ species were 25% better than those of the films etched with HF. The effect of etching time and temperature on $\text{Ti}_3\text{C}_2\text{T}_x$ formation in a 1 mol/L solution of various bifluoride compounds was investigated by Feng et al. [49]. Exfoliation of Ti_3AlC_2 in a 1 mol/L bifluoride solution at 60 °C began at least 8 h after the solution was added. To produce $\text{Ti}_{n+1}\text{C}_n\text{T}_x$ from $\text{Ti}_{n+1}\text{AlC}_n$ (where n is equal to 1 or 2), Wang et al. suggested an etching process including iron fluoride and hydrogen chloride [50]. Ti_3C_2 produced by FeF_3/HCl has a reduced fluorine concentration compared to that of Ti_3C_2 produced by HF etching. The partial oxidation of $\text{Ti}_3\text{C}_2\text{T}_x$ may be controlled by varying the immersion period in water, creating a composite of anatase and $\text{Ti}_3\text{C}_2\text{T}_x$. Compared to hydrofluoric acid, the fluoride salts used to make $\text{Ti}_3\text{C}_2\text{T}_x$ are softer and less toxic. Future structural improvements may be possible with this $\text{Ti}_3\text{C}_2\text{T}_x$ because of its big size, low fluorine concentration, few defects, and broad interlayer spacing.

Hu et al. utilized the fluorine-free synthesis method for MXene/ $\text{Ti}_3\text{C}_2\text{T}_x$ synthesis. The fabrication process of multilayer MXenes involves a Lewis acidic molten salt reaction using the CuCl_2 molten salt-shielding method. A MAX is blended with NaCl and KCl, placed in a crucible, and covered with a mixture of NaCl/KCl/ CuCl_2 . The crucible is heated to 700 °C, leading to aluminum etching and the formation of MXenes. After heating,

the sample is cleaned with deionized water and ammonium persulfate to remove salts and copper particles, then vacuum dried (Figure 3b) [51].

3.1.3. Fluoride-Free Etching

Extended etching durations may change the characteristics of the material and cause flaws and impurity clusters, even when fluorine-free etching techniques are utilized for MXenes. When used as electrodes in supercapacitors, these challenges may impact the specific capacitance of MXenes. Various non-fluorine etching technologies have been developed by scientists to address these challenges, and these methods have been detailed [52–58]. Electrochemical etching to fabricate 2D $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes with enhanced performance has promising results. To create $\text{Ti}_3\text{C}_2\text{T}_x$ free of fluorine terminations, this method may be applied to electrolytes that do not contain fluoride. By using chloride ions with a stronger attraction to aluminum (Al), the selective etching of aluminum layers may be achieved by applying a constant voltage that breaks the Ti single bond Al bonds. An electrochemical method for stacking Ti_3C_2 using binary aqueous electrolytes was introduced by S. Yang et al. [59]. Faster disintegration of the aluminum bonds occurs during chloride-ion enhancement in the anodic etching process. After that, the erosion underneath the already-eroded anode surface is intensified by adding ammonium hydroxide. Typically, the Ti_3AlC_2 material that can be etched in the least amount of time consists of one or two layers, and its average lateral dimension is more than 2 μm . In addition, an all-solid-state supercapacitor made from the exfoliated sheets shows promising results when operated at a scan rate of 10 mV/s, with a volumetric capacitance of 439 F/cm³ and an aerial capacitance of 220 mF/cm². These results are superior to those from the standard HF etching method [60].

For the selective etching of the MAX phase, an alkali is the anticipated material to be utilized. Using the Bayer method and alkali-assisted hydrothermal techniques, Li et al. [61] progressively produced a 92% mass pure multilayer MXene. Various functional groups, such as single bond OH and single bond O, were used to terminate the Al atoms on the surface of the MXene. To do this, a Ti_3AlC_2 solution was oxidized using NaOH first and subsequently dissolved in $\text{Al}(\text{OH})_4^-$. Following this, further oxidation of the Al atoms inside the inner portion produced basic Al hydroxides ($\text{Al}(\text{OH})_3$) and fresh dehydrated oxide hydroxides ($\text{AlO}(\text{OH})$). Ti layers formed as lattice confinement, making it difficult for the insoluble compounds to react with single bond OH to generate soluble $\text{Al}(\text{OH})_4^-$. This reaction necessitated elimination since it could hinder the production of the MXene. Under testing conditions of 2 mV/s, its gravimetric capacitance was 314 F/g. This number is 214.0% higher than the value of HF- $\text{Ti}_3\text{C}_2\text{T}_x$ and 28.2% higher than $\text{LiF} + \text{HCl-Ti}_3\text{C}_2\text{T}_x$ clay (with a 75 μm thickness) [62,63].

Chen et al. utilized electrochemical etching to produce d- $\text{Ti}_3\text{C}_2\text{T}_x$ (EE- $\text{Ti}_3\text{C}_2\text{T}_x$), as shown in Figure 3c. Two identical Ti_3AlC_2 blocks were employed as symmetric electrodes at 5.5 V for 5 h. The Ti_3AlC_2 cathode stays intact during etching, while the anode is primarily eaten. Because Cl^- ions interact strongly with Al, heated Cl-containing electrolytes may etch Al. Due to OH^- ion reactivity with Al, alkali solutions may also etch Ti_3AlC_2 . Therefore, the study used a hybrid aqueous etching solution with Cl^- and OH^- . Al was removed first because Ti–C bonds better than Ti–Al. Li^+ ions were also injected into the electrolyte to intercalate into the $\text{Ti}_3\text{C}_2\text{T}_x$ layers, decrease layer contacts, and increase interlayer space, which promotes etching and m- $\text{Ti}_3\text{C}_2\text{T}_x$ delamination. Thus, sonification alone was able to delaminate m- $\text{Ti}_3\text{C}_2\text{T}_x$ without utilizing harmful organic intercalants such as tetramethylammonium hydroxide or dimethyl sulfoxide. Therefore, this process was simpler and faster than earlier electrochemical etching procedures. EE- $\text{Ti}_3\text{C}_2\text{T}_x$ disperses nicely in water, as demonstrated in Figure 3d.

Additionally, the dispersion has a Tyndall effect, indicating ultralow thickness and hydrophilicity. EE-Ti₃C₂T_x also forms films well. Figure 3e shows that vacuum-filtered EE-Ti₃C₂T_x material is flexible and can be folded without breaking [64].

3.2. Sublimation Method

Using molten cryolite at around 960 °C, particular studies effectively removed Si layers from Ti₃SiC₂. In addition, TiC_x was created by sublimating indium sheets from Ti₂InC at about 800 °C in a vacuum [65–67]. In contrast to their two-dimensional precursors, the resultant carbides have a three-dimensional cubic structure due to treatment parameters, including gas composition and temperature. In addition, their phase diagram demonstrates that transition metal carbides can only maintain their non-stoichiometric structure at temperatures below 800 °C [67]. Given the possibility of MXenes forming 3D structures, all heat-treatment and synthesis operations must occur at temperatures below these limits. Many methods have been developed to make 2D metal nitrides. Among these are the scalable salt-templated synthesis approach for MoN and the migration-booster encapsulated growth method for GaN. An earlier method included creating 2D nitrides by ammoniating 2D hexagonal oxides. W₂N and V₂N are two other 2D nitrides synthesized using this method [68,69]. Two-dimensional Mo₂N and V₂N were synthesized in 2017 by Urbankowski et al. via ammoniation at 600 °C from their corresponding 2D carbide MXenes, Mo₂CT_x and V₂CT_x, respectively, into N atoms. Although both examples used ammoniation to produce 2D nitrides, the resulting crystal structures differed. The following method included using Mo₂N to keep the MXene's structure intact, which changed V₂CT_x MXene into a phase that was partially V₂N and partially cubic VN (Figure 3f) [70].

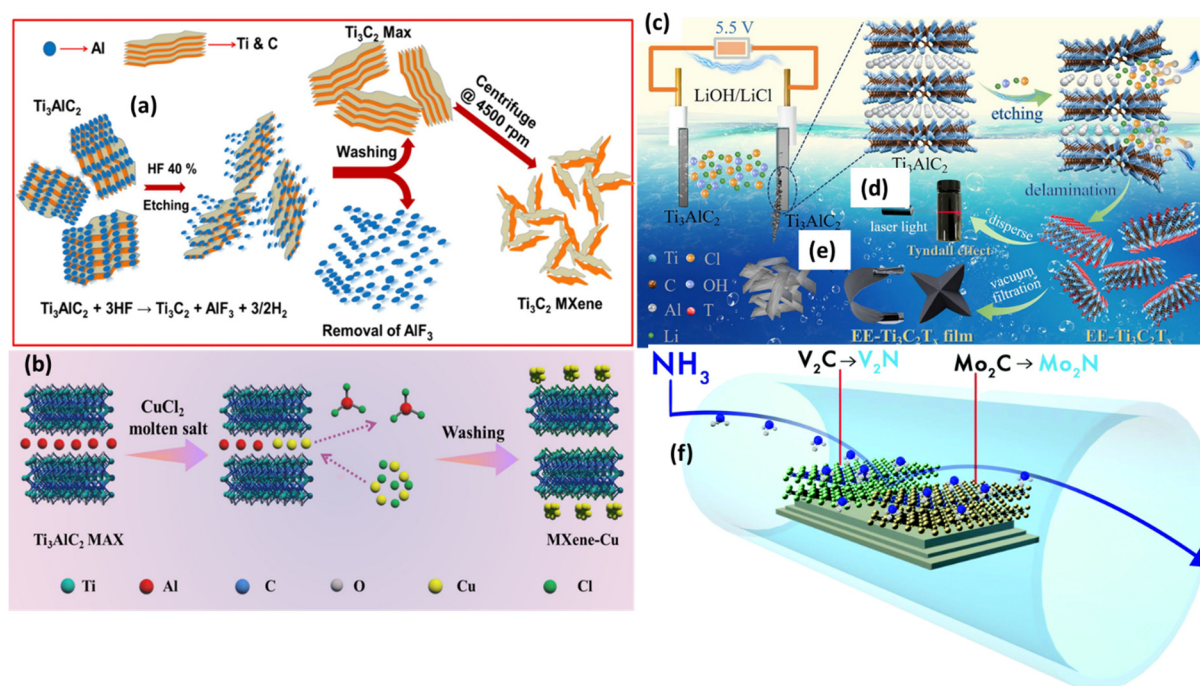


Figure 3. The synthesis of MXene by the following methods: (a) HF etching. Reprinted with permission from [46]. Copyright (2024) Elsevier. (b) Fluoride-based salt etching. Reprinted under Creative Commons CC [51]. (c) A schematic showing the steps involved in creating EE-Ti₃C₂T_x. Reprinted with permission from [64] Copyright (2022), ACS. (d) A picture of the dispersion of EE-Ti₃C₂T_x, which demonstrates the Tyndall effect Reprinted with permission from [64] Copyright (2022), ACS. (e) Images of EE-Ti₃C₂T_x photographic films. Reprinted with permission from [64]. Copyright (2022), John Wiley and Sons. (f) The electrochemical etching process. Reprinted with permission from [70]. Copyright (2017), RSC.

3.3. Chemical Vapor Deposition Method

Films, heterostructures, and functional devices may be created using chemical vapor deposition, a versatile approach for synthesizing MXenes. While CVD has effectively synthesized transition metal carbides and nitrides like Mo_2C , Mo_2N , and TiC_x , its usage in producing MXenes has been somewhat restricted [11]. This method results in uniquely shaped MXenes with accessible surfaces and catalytically active edges. The synthesis of MXenes includes heating a mixture of CH_4 , TiCl_4 , and Ar gas on a Ti surface to 950°C . During characterization, the synthesis of Ti_2CCl_2 MXene was confirmed by comparing the lattice characteristics and Raman spectra to values that had been previously published [11].

Wang et al. showcased a straightforward synthetic approach for the large-scale and efficient synthesis of MXenes, encompassing phases that have yet to be derived from MAX phases through the reactions of metals and metal halides with graphite, methane, or nitrogen (Figure 4A). Different characterization techniques like X-ray diffraction (XRD) (Figure 4B), Raman spectroscopy (Figure 4C), scanning electron microscopy (SEM) (Figure 4D), and high-resolution high-angle annular dark field (HAADF) and electron energy loss spectroscopy (EELS) elemental maps (Figure 4E) showed the synthesis of MXene by the CVD method efficiently [25].

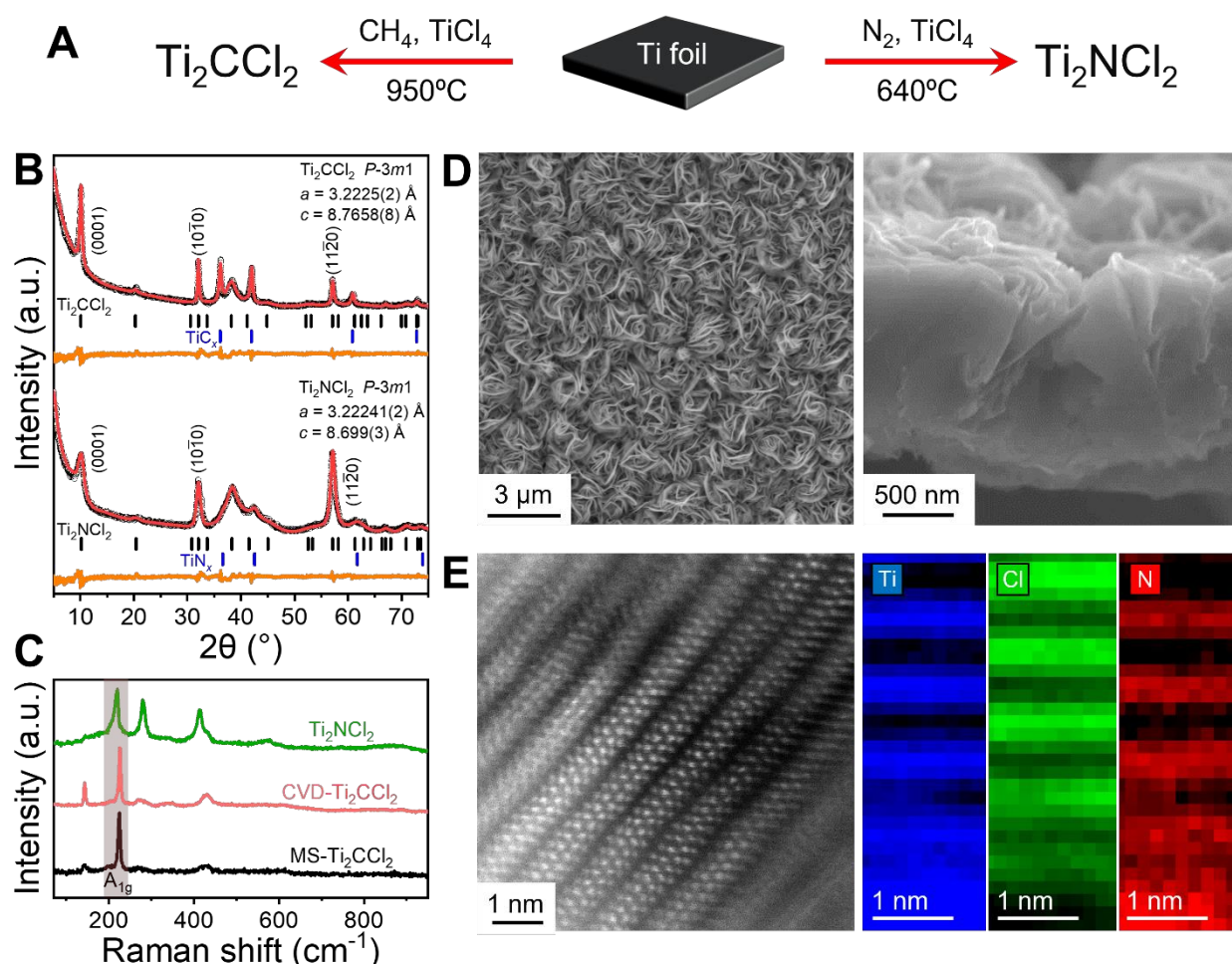


Figure 4. The growth of MXenes via CVD. (A) A visual representation of the CVD processes. (B) The XRD patterns and Rietveld refinement results for CVD- Ti_2CCl_2 and CVD- Ti_2NCl_2 . (C) The Raman spectra of CVD- Ti_2CCl_2 and CVD- Ti_2NCl_2 MXenes compared to those of a conventional material. (D) Frontal and cross-sectional SEM images of CVD- Ti_2CCl_2 . (E) High-resolution HAADF photographs and the EELS elemental distribution of CVD- Ti_2NCl_2 . Reprinted with permission from [25]. Copyright (2023), Science.

Researchers discovered that Ti_2CCl_2 MXene production starts at around $850\text{ }^\circ\text{C}$ and peaks at $950\text{ }^\circ\text{C}$. At temperatures beyond $1000\text{ }^\circ\text{C}$, TiC_x became the principal by-product of the process. The Ti_2CCl_2 phase was seen after two hours at $950\text{ }^\circ\text{C}$, and the end products had a rather consistent ratio of Ti_2CCl_2 to TiC_x . The reaction duration was prolonged from two hours to ten days at this temperature. One may ask whether thermodynamics or kinetics had a more significant role in the development of MXenes. Notably, attempts to create the MXene phase by reacting TiC_x with Ti and TiCl_3 or TiCl_4 were unsuccessful. However, when pure MS- Ti_2CCl_2 was heated to $950\text{ }^\circ\text{C}$ for a long time, it partially transformed into TiC_x . These results led the authors to conclude that Ti_2CCl_2 was a competitive product with TiC_x and had a stronger kinetic preference [20,25].

3.4. Hydrothermal Method

Producing MXene components on a wide scale with different designs is made extremely easy by using the hydrothermal method, eliminating the need to expose workers to dangerous HF vapor. Furthermore, it poses no threat to the environment. The MAX technology eliminates the need for fluorine hydrothermal treatment in its innovative leaching technique, allowing for the creation of aluminum layers. A hydrothermal solution of sulfuric acid is used for 1.5 h at $85\text{ }^\circ\text{C}$ and a concentration of 1 mol/L after immersing the Ti_3AlC_2 material in an aqueous NaOH solution for 100.0 h [71]. An alternative method for studying Ti_3AlC_2 anodic corrosion in an aqueous binary electrolytic solution has been suggested. Another technique for producing $\text{Ti}_3\text{C}_2\text{T}_x$ via hydrothermal chemical means is to first immerse microscopic Ti_3AlC_2 particles in a water solution containing ammonium fluoride. Previous studies have shown that hydrothermal etching can successfully produce Nb_2C and Ti_3C_2 , circumventing the drawbacks of HF direct-etching [72]. Improving the lattice parameter, boundary electron transport surface area distribution, maximum distance between 2D MXene layers, and simplicity of the sonication-induced exfoliation pattern are critical for optimizing adsorption performance. These further advantages are present in Ti_3C_2 that is synthesized via the hydrothermal method. Using Baeyer's approach and an alkali-induced hydrothermal procedure, high-purity multilayered $\text{Ti}_3\text{C}_2\text{T}_x$ was synthesized for the first time. Achieving 90% purity was helped along by the presence of zero-terminated fluoride ions. The production of MXenes without fluoric acid is now the subject of inquiry. These methods include chemical vapor deposition, salt-template, and molten salt methods. Using efficient and realistic contemporary methodologies is essential while developing adsorbent materials based on MXenes. These techniques are critical for optimal specific surface distribution, well-defined chemical stability, and control over surface functional groups. Several environmental concerns are the targets of these efforts [73,74].

3.5. Ultrasonic Synthesis

The ultrasonic synthesis method for MXenes has been extensively explored in recent years, providing a facile and efficient approach for the production and modification of these 2D materials.

Ultrasonication at controlled temperatures can achieve N-doping in MXenes, enhancing their hydrogen evolution reaction (HER) activity by forming TiN bonds. For instance, optimal conditions, like a $35\text{ }^\circ\text{C}$ ultrasonic temperature, yield high concentrations of TiN bonds, significantly reducing overpotential and improving catalytic efficiency [75]. Ultrasonication facilitates the synthesis of MXene-based nanohybrids, such as $\text{NiFe}_2\text{O}_4/\text{MXene}$ and $\text{CuFe}_2\text{O}_4/\text{MXene}$, enhancing properties like photocatalytic and antibacterial activities. These nanohybrids exhibit improved dye degradation and pollutant removal due to an increased surface area and the better dispersion of MXene sheets [76,77].

Utilizing the selective etching of Ti_3AlC_2 in an HF solution combined with ultrasonic treatment, $\text{Ti}_3\text{C}_2\text{T}_x$, where T_x represents a F^- or OH^- -group, was produced by Arlashkin et al. The primary stages involved in the etching and intercalation of MXene-type layered structures have been identified and elucidated, encompassing the formation of transcrystalline cracks in MAX phase crystals, the separation of MXene packages, the emergence of the layered structure, and the complete delamination resulting in the formation of individual $\text{Ti}_3\text{C}_2\text{T}_x$ plates. The optimal degree of separation was seen in the sample subjected to 6 h of ultrasonic treatment with HF solution followed by an additional 2 h of ultrasonic treatment. These results indicate that ultrasonic treatment enhances the etching rate of the original precursor and amplifies the degree of delamination [78].

3.6. Ball Milling

The ball milling method has been increasingly utilized for the synthesis of MXenes due to its efficiency in material modification and size reduction. Ball milling with additives like red phosphorus enables the reducing of MXenes to nanoscale dimensions (~6 nm). This process involves chemical interactions between surface groups (e.g., oxygen) and the additive, enhancing properties for energy storage applications such as sodium-ion batteries [79]. Ball milling has combined ZnO with MXene to enhance the adsorption and photocatalytic degradation of pollutants in water. The increased surface area and pore structure resulted in 95.19% dye removal efficiency under visible light [80].

Bian et al. synthesized MXene@BN by the ball milling method. MXene and BN were introduced into an agate ball mill containing 300 mL of a 5:1 solution of ethanol and deionized water. Milling was conducted using a planetary ball mill at 800 rpm for a duration of 48 h. Thereafter, the products from the ball mill were subjected to freeze-drying using a freeze-dryer to yield MXene@BN powder [81].

3.7. Pyrolysis

Through a gelation and pyrolysis process, single-metal catalytic sites have been anchored onto N,P-co-doped 3D porous MXene structures. These materials exhibited superior catalytic activity for hydrogen evolution reactions due to enhanced charge transfer and optimized electronic structures [82]. Using the minimal intensive layer delamination (MILD) technique, $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets were obtained by selectively etching the Al layer in MAX Ti_3AlC_2 powder with LiF/HCl . Hydrogen bonding and van der Waals forces allowed the $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets to be securely adsorbed onto PMMA microspheres, producing PMMA@MXene (PM) microspheres. Co^{2+} adsorption sites abound on $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets due to the negative charges provided by the several terminal functional groups ($-\text{F}$, $-\text{OH}$, $=\text{O}$). By growing ZIF-67 nanoparticles on the surface of PM microspheres in situ, PMMA@MXene@ZIF-67 (PMZ) microspheres are produced when dimethylimidazole is added. The final product of two hours of pyrolysis in an argon atmosphere with varied temperatures is microspheres made of hollow $\text{Co}_3\text{O}_4/\text{Co}/\text{NC@MXene}$. As the Co^{2+} ions are reduced during pyrolysis, the PMMA templates are also destroyed [83]. Table 1 explains the advantages and disadvantages of synthesis methods for MXenes discussed in the review.

Table 1. Advantages and disadvantages of synthesis methods for MXenes.

Synthesis Method	Advantages	Disadvantages	References
Selective Etching	- Effective at creating MXenes with minimal layers.	- Requires hazardous chemicals like HF, posing safety risks.	[84]
	- Allows precise control of surface terminations (e.g., hydroxyl, fluoride).	- Wrinkling of MXene flakes at low pH may occur.	
	- High flexibility in tuning electrochemical properties.	- Time-consuming, and efficiency depends on etching time and agitation.	
	- Suitable for MAX phases containing aluminum.	- Fluoride etching affects material quality and environmental stability.	
Fluoride-Based Salt Etching	- Less toxic compared to HF etching.	- MXenes produced may still have some fluorine-related surface terminations, affecting performance.	[85]
	- Larger, better-quality MXene flakes.	- HF-based etching, though reduced, may still be required in some cases.	
	- Potentially improves ion transport for energy storage applications.	- Limited to specific MXene types.	
Fluoride-Free Etching	- Safer and less toxic (no fluorine involvement).	- More defects can be introduced, affecting performance.	[86]
Gas-Phase Etching	- Can enhance material properties like water dispersibility and supercapacitor applications.	- Extended etching time may cause impurity clusters and changes to material properties.	[87]
	- Solvent-free and scalable process.	- Requires high temperatures and complex setup.	
	- Lower risk of handling dangerous chemicals compared to wet etching methods.	- Limited MXene types can be synthesized this way.	
	- Can lead to more homogeneous etching and control over structure.	- Produces gaseous by-products, requiring careful containment.	
Hydrothermal Method	- Safer and more environmentally friendly (no HF involved).	- Limited to certain MXene types and requires long synthesis times.	[11]
	- High purity of final product.	- Limited control over layer structure and size.	
	- Allows synthesis without needing fluorine-based etchants.	- May still face challenges in scaling for larger production.	
Sublimation Method	- Allows for high-temperature synthesis of MXenes.	- Higher energy costs due to need for high temperatures (up to 960 °C).	[88]
	- Useful for removal of non-metallic elements.	- Potential phase changes and structural alterations in the material.	
Chemical Vapor Deposition (CVD)	- High control over MXene shape and structure.	- Complex and expensive setup.	[89]
	- Allows for production of MXenes with active catalytic edges.	- Limited success in synthesizing wide range of MXenes.	
	- Ideal for creating films and heterostructures.	- May result in unwanted by-products such as TiC _x at high temperatures.	

4. Modifications to MXenes and Their Effects on Their Properties

4.1. Surface Modification Effects on MXene Properties

The poor interface binding strength that arises from the restricted compatibility between MXenes and hydrophobic polymers significantly impacts their overall mechanical qualities. It could be challenging to meet the performance requirements for specific application areas due to the small diversity of hydrophilic functional groups. For instance, opposing electric terminal groups (^-F , ^-OH) make electrical energy storage inefficient because they hinder the diffusion of Li^+ and Na^+ ions and the mobility of electrolyte ions. The ability of a MXene-based battery to store energy is significantly reduced as a result of this [90]. Hence, controlling the MXene interface relies heavily on altering the MXene surface (Figure 5) [91].

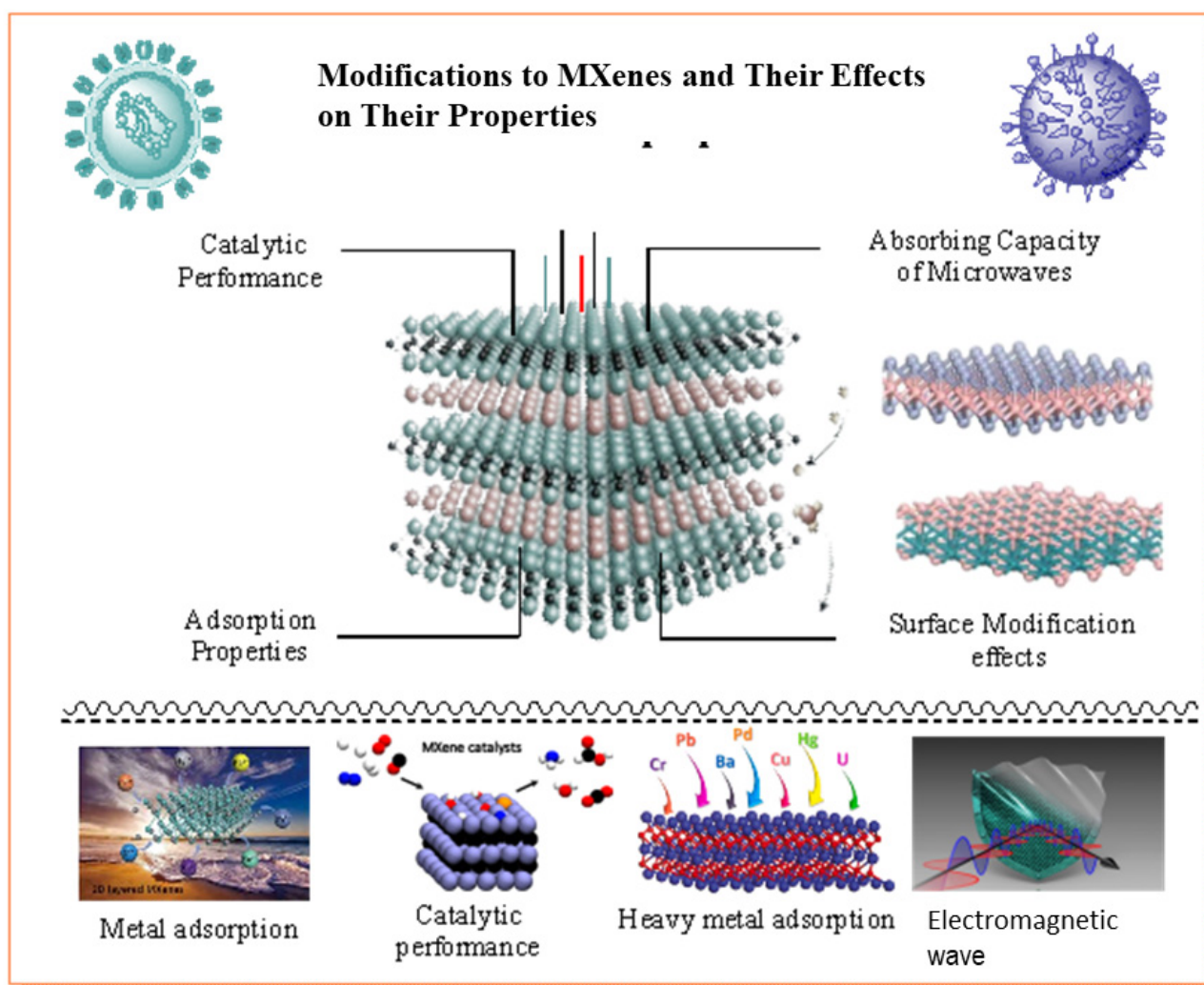


Figure 5. Modifications to MXene. Adapted with permission from [91]. Copyright (2017) John Wiley and Sons.

It is possible to change the properties of a MXene by modifying its surface. Its unique properties define a surface's friction and adhesion capabilities. The presence of negative friction factors enhances the hydrophilicity and adhesivity of a MXene. The strength–friction interaction may be amplified by the hydrophilicity of the MXene surface. Changes in surface electrostatic potential affect MXenes' electronic structure and work function. The number of states and the work function are considerably affected by surface groups [92,93]. Researchers have examined how different N-doping modes and procedures affect the elec-

trical properties of MXene structures [94]. Surface adsorption, functional group substitution, and lattice substitution are the three possible ways to introduce N-doping. Interfacial nucleophilic addition and repeated condensation procedures incorporate alkyl phosphoric acid ligands into the aqueous phase. Consequently, a Ti-O-P connection is formed, and it subsequently adheres to the surface of the MXene. The solvation effects of strong nonpolar forces and the spatial stability of long alkyl chains boost the solubility of MXenes in nonpolar organic solvents [95].

4.2. Factors Influencing MXenes' Catalytic Performance

The capacity to split and transmit charges and excellent electrical conductivity are advantageous properties of MXenes. Because of these characteristics, MXenes may be used as catalysts in photocatalytic processes. Photocatalysis for CO₂ reduction, photodecomposition for hydrogen production, and photodegradation for organic pollutant degradation are only a few potential applications. The extensive use of MXenes in catalysis has led to the implementation of several optimization strategies to boost the efficiency of these functional material catalysts.

To enhance the surface functional groups, Ti₃C₂ was treated with plasma. Photocatalytic reactions benefit from the abundance of active sites on the surface of MXenes resulting from the enhanced surface functional groups on these materials [96]. Ti₃C₂O₂ MXenes provide the highly selective photocatalytic reduction of CO₂ due to oxygen vacancies inside the material. In situ production of TiO₂ nanoparticles on highly conductive MXenes Ti₃C₂ has been achieved by calcination [97]. By evenly dispersing nanoparticles on Ti₃C₂, an extraordinary structure resembling the rice husk was accomplished. Compared to commercial TiO₂, the optimized TiO₂/Ti₃C₂ composite produced 3.7 times more CH₄ and was 3.7 times more effective in photocatalytic CO₂ reduction. Increased photocatalytic activity is seen when a double heterojunction is present, namely an S-type heterojunction at the TiO₂/C₃N₄ interface and a Schottky heterojunction at the C₃N₄/TCQD interface. This double heterojunction may separate, migrate, and use the substantial redox capacity of the electron-hole pairs produced by light. Studies conducted in the past have shown this impact [98]. Optimizing performance is achieved by modifying the MXene to increase its photoactivity. Multiple investigations have demonstrated that MXenes significantly improve the catalyst's efficacy [99]. Due to its light-shielding qualities, however, an excess of black MXene reduces photoactivity. As a cocatalyst, Ti₃C₂ increases semiconductors' CO₂ reduction efficiency. Composite catalysts improve the efficiency of CO₂ reduction and conversion by including extra semiconductors in the form of quantum dots [100].

Regarding dispersion in liquid, zero-dimensional quantum dots outperform two-dimensional ultrathin nanosheets. Also, their concentration of active edge locations is greater. Using photocatalysis with Ti₃C₂ QDs/Cu₂O NWs/Cu, the CO₂ reduction process achieved a methanol production of 153.38 ppm·cm⁻², an 8.25-fold increase over Cu₂O NWs/Cu [101].

4.3. Factors Influencing the Absorbing Capacity of Microwaves

The area of microwave absorption is one where MXenes show excellent potential [102,103]. The layered nature of MXenes allows for fine-grained control over its amount of microwave absorption. Several preparation processes allow for the flexible alteration of the interlayer gap in the multilayer material. The building blocks for three-dimensional buildings are materials with one or two layers. There may be more reflections and dispersion of electromagnetic waves between materials if there is an interlayer structure. Due to their high conductivity, MXenes experience a significant decrease in dielectric and polarization properties [103]. Magnetic loss may occur in certain species, especially MXenes

that include Cr and Mn. Due to the interface reflection of the high-impedance matching differential, the material's electromagnetic capacity and impedance matching are both enhanced by MXene's high conductivity. When combined with other chemicals, MXenes may improve their microwave absorption properties.

MXenes' light-absorbing capabilities might be enhanced by adding a trace quantity of TiO_2 atop Ti_2CT_x . Due to its dipolar polarization capacity, voids, and significantly increased electrical conductivity, Ti_3CNT_x exhibits outstanding microwave absorption capabilities during annealing. It is possible to improve the ability to absorb electromagnetic waves and enable many reflections by building structures with unusual morphologies, such as three-dimensional porous structures, multilayer wave absorption structures, shell structures, floral structures, etc. One possible solution to the problems of weight and reflections is to build a single-material structure out of magnetic particles that are hollow, porous, or shell-shaped, rather than solid [104].

4.4. Factors Influencing Adsorption Characteristics

The unusual layer structure and surface properties of MXenes provide adsorption capabilities, making them very promising for various applications. Consequently, MXene is used to lessen the concentrations of organic pollutants and heavy metals. With great sensitivity and remarkable reversibility, Ti_3C_2 adsorbs the heavy metal Pb^{2+} quickly and abundantly. This phenomenon becomes much more noticeable when alkali metal intercalation is present [105,106]. You can put additional chemical compounds like urea and methylene blue into MXenes since they can be inserted and separated into nanosheets. As a result, MXene shows promising adsorption capabilities for wastewater treatment by removing pollutants and heavy metals. It is possible to improve MXene's adsorption capabilities during catalytic processes by modifying its surface functional groups.

MXene modifications might improve the efficiency of heavy metal removal. Sodium-ion alkalization-grafting using a silane coupling agent has been the most effective alteration method up to this point. Using less adsorbent (0.1 g/L) and a shorter equilibrium time (30 min), this method achieved a greater adsorption capacity (385 mg/g). An essential step in the adsorption process is ion exchange, which involves binding to the surface of MXene functional groups and replacing heavy metal ions. The pH affects the rate of Pb^{2+} adsorption by alkylated $\text{Ti}_3\text{C}_2(\text{OH}/\text{ONa})_x\text{F}_{2-x}$, with a higher sorption affinity seen at pH values between 5 and 7. The weak attraction of MXenes to Pb^{2+} ions in acidic environments may cause the re-formation of Pb^{2+} ions from used flakes in the solutions. Heavy metal removal at different pH levels, adsorbent concentrations, beginning concentrations, adsorption temperatures, and contact durations was the subject of an inquiry. Exploring the purpose and uses of MXene design should be prioritized, nevertheless, since it has the potential to significantly enhance adsorption capacity [107].

5. Photocatalytic Degradation of Pollutants

For photocatalysis, particularly in the visible spectrum range, 2D materials like metal–organic frameworks, black phosphorous, graphene, layered double hydroxides, and graphitic carbon nitride have recently attracted a lot of research interest [108]. However, due to their exceptional properties, nanomaterials based on MXene are attracting more attention than typical 2D materials. The unusual, layered structure of MXenes allows them to have an enormous surface area and considerable interlayer spacing. Several photocatalytically advantageous active sites are accommodated by this arrangement [109]. Compared to other 2D materials, including reduced graphene, MXene stands out due to its remarkable thermal, chemical, and mechanical stability (Figure 6).

Furthermore, MXenes outperform carbon-based nanomaterials and reduce graphene oxide in terms of electrical properties, and they are very similar to graphene oxide nanomaterials [110]. Graphene does not possess the unique ability to serve as a hole acceptor in photocatalytic applications, whereas MXenes do [109]. The rates at which charges recombine are reduced because this enhanced electrical conductivity makes charge separation and transfer easier. Ti_3C_2 MXene may absorb visible light because it has appropriate bandgaps. Because of its hydrophilic nature and negative surface charge, it is a strong candidate for photocatalytic applications [111]. MXenes' terminal functional groups are open to change throughout the photocatalytic reaction and manufacturing procedures. According to previous studies, -F terminations may replace -O or -OH groups in hydrothermal processes [112,113]. Calcination, on the other hand, can change -OH terminations into -O terminations. These changes significantly affect the surface properties and electrical configuration of MXenes, affecting how they participate in charge transfer in composite photocatalysts that include MXenes. Liu et al.'s study emphasizes how these surface terminal groups significantly affect the Fermi level and work function of MXenes [114]. Biswal et al. set out how effective modified MXenes are in photocatalytically degrading specific pollutants [115]. Compared to unmodified MXene and MXene with -F functional groups, MXene with -O functional groups on its surface shows a greater ability to absorb light. In particular, the -O functional group outperforms the -OH and -F functionalities regarding visible-light absorption and reflection. Because -O atoms favorably affect the density of states near the Fermi energy level, this may be why -OH/-F surface functional groups absorb light more efficiently than -O functional groups.

Depending on the configuration of the -F groups, MXenes terminated with these groups may exhibit metallic or semiconductive properties. In a work conducted by Wei et al., MXene with -F termination was alkaline-treated into MXene with -OH termination. The researchers compared the adsorption capacities of the two varieties of MB. The adsorption capacity of the Ti_3C_2 MXene treated with alkaline was much higher than that of the original MXene. This finding might be explained by the -OH and -F termination groups on MXenes, which have been shown to affect photodegradation and highlight the complex interplay between surface functional groups and photocatalytic activity [116].

Additionally, Schottky junctions are formed when the termination groups participate in chemical interactions with semiconductors between phases [117]. With the help of the Schottky barrier, photoinduced electrons can only go in one direction from the semiconductor's conduction band to Ti_3C_2 MXene. This suggests that MXene may take electrons and enhance charge carrier separation via the Schottky barrier [118]. The exposed terminal metal sites in MXenes operate as photocatalytic active sites [119]. An appealing option for photocatalysis, MXenes have unique physicochemical properties that are absent in ordinary materials.

The first work to record the dye-induced breakdown of Ti_3C_2 MXene was conducted by Mashtalir et al. Their results demonstrated that the cationic dye methylene blue outperformed the anionic dye acid blue 80 (AB 80) regarding UV radiation adsorption capacity [120]. One possible explanation for this result might be the electrostatic interactions between the surface charges of the MXene and the MB dye. Ti_3C_2 MXene is a photocatalyst that reduces the molecular weight of MB by 81% and AB by 62% when subjected to UV light. Regardless, MXenes are not particularly efficient because of their short manufacturing run, lack of semiconductivity, propensity for sheets to restack, and quick oxidation. By forming binary or ternary systems with semiconductors with the appropriate conduction band and valence band potentials, MXenes may be more suited for photocatalytic applications, overcoming these restrictions. These altered heterostructures are anticipated to

exhibit an enhanced bandgap, larger surface area to increase photocatalytic activity, lower recombination rate, and better separation of charge carriers.

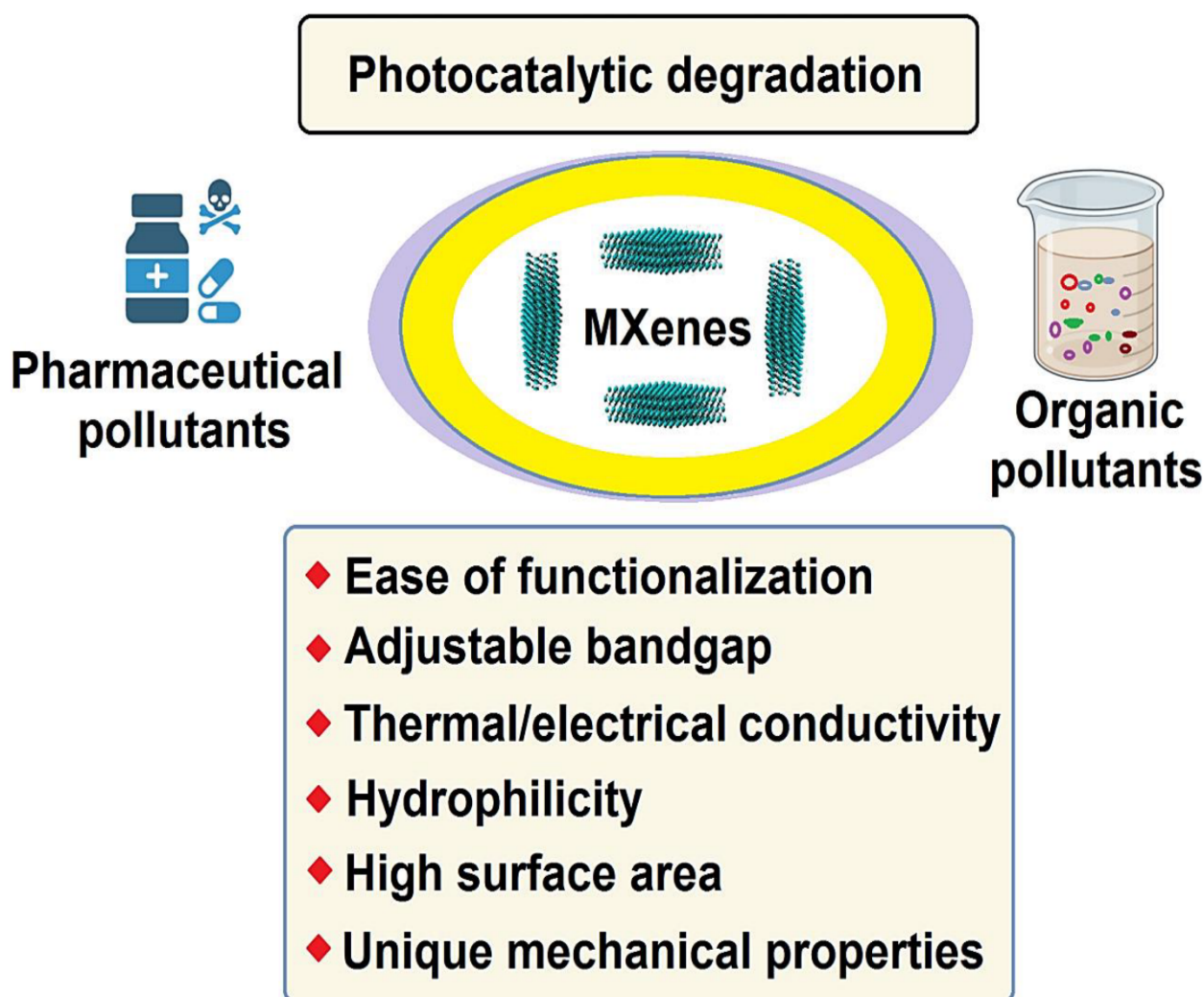


Figure 6. MXenes have unique properties for the degradation of pollutants. Reprinted with permission from [121].

5.1. Cationic Dyes

The capacity of MXenes to break down dyes has been the subject of much research. This section mainly highlights the noteworthy progress achieved in breaking cationic dyes using heterostructures based on MXenes. Anionic surface charges on Ti_3C_2 MXenes improve their affinity for cationic dyes and could weaken the $-\text{N}=\text{N}-$ bond strength in azodyes. Photocatalytic degradation of MB and RhB using MXene-based heterostructures is a common area of research for cationic dyes. By calcining $\text{Ti}_3\text{C}_2@\text{TiO}_2$, Qiaoran Liu and colleagues were able to create a heterostructure, and as a third component, they also incorporated CdS [111]. When it came to MB and RhB, the $\text{CdS}@\text{Ti}_3\text{C}_2@\text{TiO}_2$ composite showed a degradation efficiency of 100%. The existence of a Schottky junction between Ti_3C_2 and TiO_2 and the charge transmission bridge function of the Ti_3C_2 MXene layers might explain this. This connection reduces charge carrier recombination by limiting the backflow of electrons to TiO_2 . In their study on the breakdown of RhB dye, Ding et al. [122] used g- C_3N_4 and created a ternary heterojunction catalyst consisting of $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g}-\text{C}_3\text{N}_4$. The Ti_3C_2 MXene terminated with O/OH^- and TiO_2 provides extraordinary electron transport support, in contrast to g- C_3N_4 , which efficiently absorbs light and moves electrons

into the conduction band. It was suggested that active surface area and pore size be improved, TiO_2 and Ti_3C_2 MXene create n-type Schottky heterojunctions, and that $\text{g-C}_3\text{N}_4$ and TiO_2 form n-n heterojunctions. The presence of the stated heterojunctions allowed for the effective separation of the charge carriers.

Graphene sheets bound to a $\text{TiO}_2/\text{g-C}_3\text{N}_4$ photocatalyst were produced using a one-step in situ calcination procedure. The photocatalytic degradations of ciprofloxacin, bisphenol A, tetracycline, and RhB were then assessed using the resultant material. When exposed to light, $\text{g-C}_3\text{N}_4$ effectively generated charge carriers, while graphene served as a photosensitizer. There were active species, such as $\cdot\text{O}_2$ on the $\text{g-C}_3\text{N}_4$ conduction band and $\cdot\text{OH}$ free radicals on the TiO_2 valence band, which caused the degradation to occur [123]. Furthermore, other studies have been carried out on photocatalytic dye degradation using heterostructures of transition metal oxide/MXene [124]. There are various uses for TMOs due to their advantageous optical, electrical, mechanical, chemical, and thermal properties. Additionally, they have a wide bandgap, several active sites, and excellent diffusion efficiency [125,126]. But, on occasion, they show signs of light dispersion, diminished sensitivity to light, a propensity for light-induced corrosion, and quick charge recombination. By building heterostructures employing MXenes, these constraints might be partially alleviated.

Several studies have explored the possibility of using ZnO/MXene composites to degrade various colors. A novel kind of rice-crust-looking $\text{ZnO}/\text{Ti}_3\text{C}_2\text{T}_x$ MXene material was recently developed and reported in research by Hoai Ta et al. Calcination was the method of choice for synthesizing this substance. According to their findings [126], this substance could break down 99.8 percent of RhB (a dye) in only 70 min. Some possible explanations for the improved efficiency of $\text{ZnO}/\text{Ti}_3\text{C}_2\text{T}_x$ are as follows: (1) a low recombination rate and a large output of charge carriers resulting from creating a Schottky junction; (2) this material has a smaller bandgap (approximately 1.6 eV) than ZnO .

A simple hydrothermal and chemical deposition approach produces an MXene heterojunction by hybridizing ZnO and Ag nanoparticles with the MXene ($\text{Ag@ZnO@Ti}_3\text{C}_2$ ternary composite) by Liu et al. To boost the photocatalytic activity of MXene, the combination of Ag and ZnO may effectively compensate for its narrow bandgap, separate the charge carriers, and increase the absorption of visible light. One way to measure the AZM's photocatalytic activity is to see how well it removes methylene blue dye and levofloxacin when exposed to visible light. Figure 7a shows that even after 50 min of dark stirring, the MB concentration had not dropped much, suggesting that the adsorption interaction between methylene blue and the hydrocarbons and anions present was mild. After 50 min of visible-light irradiation, the MB elimination rate was 8.31% without a photocatalyst. This is likely because the spectra of the light emitted by the irradiation coincides with the MB peak absorbance. Figure 7a,c show that when it comes to MB and LVX photodegradation performance, the ZM composite is better than pure MXene. Because of the Ag particles' SPR impact, the AZM samples show much better photocatalytic degradation than the ZM samples. Figure 7b,d provide a rate graph that plots $\ln(C_0/C)$ against time to better quantify the deterioration rate [127]. The primary species involved in the photodegradation of MB and LVX, as shown by the outcomes of trapping tests and EPR, are $\cdot\text{OH}$ and $\cdot\text{O}_2^-$. This study offers a means to develop novel bandgap photocatalysts that can degrade organic pollutants photocatalytically, which may help reduce environmental pollution.

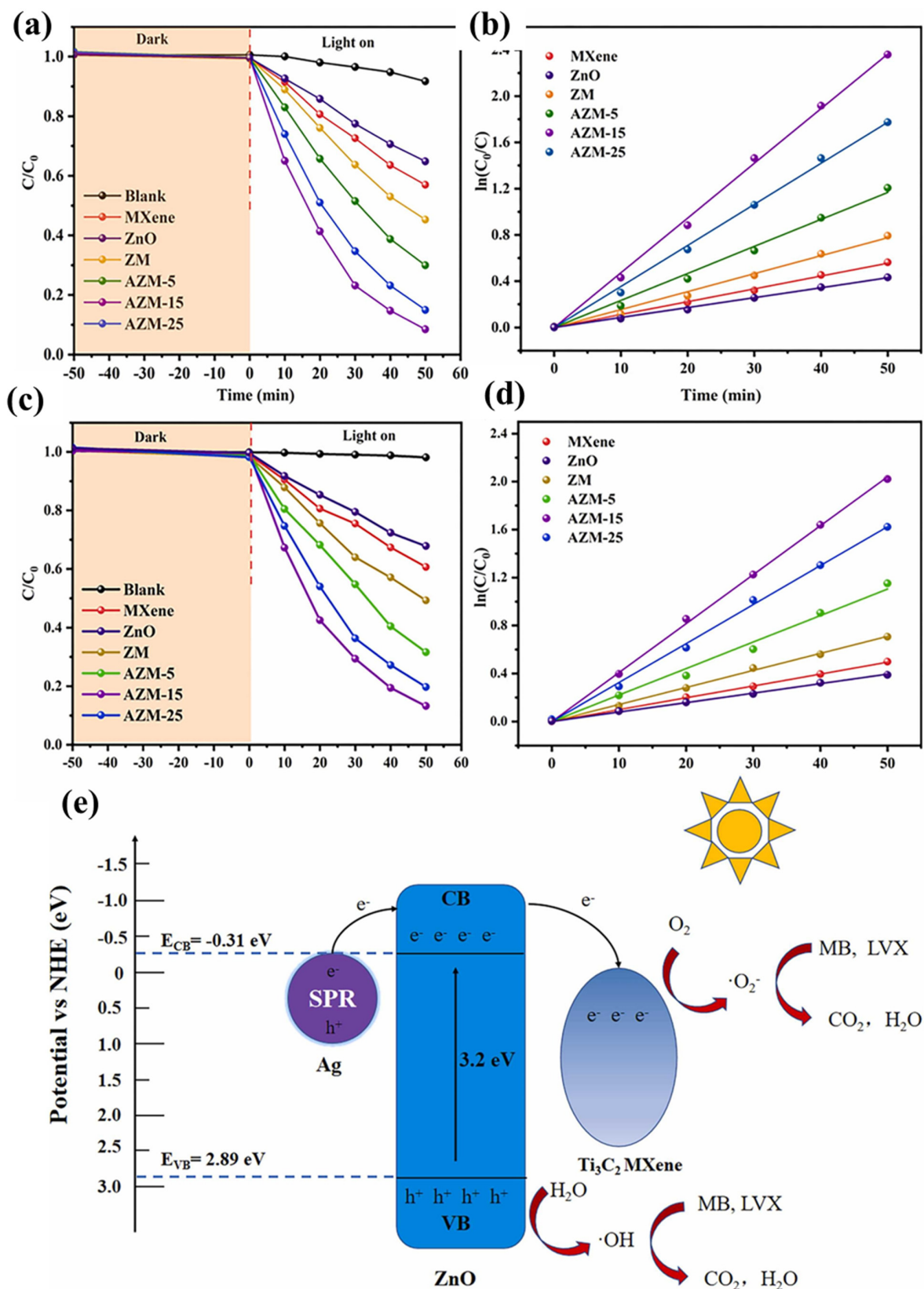


Figure 7. The photocatalytic degradation of (a) MB and (c) LVX using different photocatalysts when exposed to visible light. The corresponding $\ln(C_0/C)$ versus time plots for (b) MB and LVX (d) antibiotics are also presented. (e) The charge transfer mechanism of the material. Reprinted with permission from [127]. Copyright (2023) Elsevier.

To improve dye degradation, scientists have looked at other alternatives to MXene that might create heterojunctions. Bismuth oxyhalides' remarkable electric and optical properties and two-dimensional plate-like structure have made them significant players in photocatalysis. Nevertheless, their prospective usefulness is limited by these molecules' large energy gaps. Researchers have investigated several heterostructures that use bismuth oxyhalides to circumvent this constraint. Liu et al. [128] synthesized $\text{Ti}_3\text{C}_2/\text{BiOCl}/\text{TiO}_2$ heterojunctions and showed that they could photocatalytically destroy RhB. Because of their large energy gaps, pure bismuth oxychloride and titanium dioxide can only absorb light in ultraviolet conditions. The intercalation of the MXene increased the catalyst's capacity to capture visible light. Experiments using RhB degradation were shown to be primarily driven by h^+ and $\bullet\text{OH}$, as revealed by active species trapping. Using a straight-forward reflux method, Liu et al. [129] produced $\text{BiOBr}/\text{Ti}_3\text{C}_2$, a bismuth oxyhalide hybrid composite. The degradation of RhB was used to assess the photocatalytic efficacy. More proof was provided that BTC outperformed pure BiOBr because the absorption rate rose in correlation with the amount of Ti_3C_2 MXene in the composite. Using a hydrothermal approach, Xu et al. developed a ternary system, $\text{BiOBr}/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{Tx}$. This system outperformed earlier ones in terms of RhB degradation efficiency, coming in at 99.8 percent [130]. A clear heterojunction between the TiO_2 nanoparticles and the BiOBr nanosheet allowed for the better migration of the photoinduced charge carriers.

Furthermore, MXene is an appealing catalyst for RhB degradation due to its high electron-trapping efficiency and the synergistic effects of the heterojunction. RhB was treated with BiOBr , $\text{TiO}_2/\text{Ti}_3\text{C}_2\text{Tx}$, and $\text{BiOBr}/\text{TiO}_2/\text{Ti}_3\text{C}_2\text{Tx}$ for photodegradation. Ke et al.'s synthesized $\text{BiOI}/\text{TiO}_2/\text{Ti}_3\text{C}_2$ showed exceptional effectiveness in RhB degradation [131]. The deposition of BiOI nanoflakes followed the in situ growth of (001) TiO_2 on Ti_3C_2 MXene. When n-type TiO_2 and p-type BiOI are joined by a Schottky junction and a p-n junction between TiO_2 and Ti_3C_2 MXene, recombination may be hindered, and charge carriers can be better separated.

Catalysis relies heavily on spinel ferrites (MFe_2O_4 ; M = divalent metal ions such as Ni^{2+} , Co^{2+} , Cu^{2+} , Zn^{2+} , or Fe^{2+}) because of their remarkable electrical properties, biocompatibility, and durability. Due to clustering, ferrites have a low surface area, although they exhibit intermolecular interactions and possess a strong magnetic field. Therefore, heterostructures made of several semiconducting materials are advantageous. Some nanohybrids, such as $\text{CuFeO}_3/\text{Ti}_3\text{C}_2$ and $\text{NiFe}_2\text{O}_4/\text{Ti}_3\text{C}_2$, have been used to study MB deterioration. One possible explanation for the enhanced degrading efficiency is the creation of a Schottky heterojunction involving Ti_3C_2 and ferrites. The buildup of h^+ in MXene occurs because the Schottky barrier prevents the reverse flow of h^+ . To degrade RhB and absorb Cr(VI) [76,77,132], Zhang et al. created a ternary system using lamellar $\alpha\text{-Fe}_2\text{O}_3/\text{ZnFe}_2\text{O}_4@\text{Ti}_3\text{C}_2$. The excellent dispersion of $\alpha\text{-Fe}_2\text{O}_3/\text{ZnFe}_2\text{O}_4$ on the Ti_3C_2 MXene surface greatly enhanced the photocatalytic efficacy of 10 wt% $\alpha\text{-Fe}_2\text{O}_3/\text{ZnFe}_2\text{O}_4@\text{Ti}_3\text{C}_2$. The interface region of Ti_3C_2 MXene and $\alpha\text{-Fe}_2\text{O}_3/\text{ZnFe}_2\text{O}_4$'s strong electronic interaction promoted the separation of photogenerated charge carriers and increased efficiency.

Some studies have shown that f-orbital-carrying rare-earth ions may efficiently absorb charge carriers. The photocatalytic and very stable CeO_2 has been used in several scientific endeavors. Unfortunately, its reduced adsorption capacity and fast charge carrier recombination severely limit its usefulness. The photocatalytic degradation of RhB was achieved by Zhou et al. using Ti_3C_2 MXene that had CeO_2 added to it. In 90 min, the RhB degradation rate was 72% for the $\text{CeO}_2/\text{Ti}_3\text{C}_2$ nanocomposite, 3 times as efficient as CeO_2 and 1.2 times higher than bare Ti_3C_2 MXene. Due to its tiny bandgap, the $\text{CeO}_2/\text{Ti}_3\text{C}_2$ material exhibits significant optical absorption [133]. Because of its great endurance and resilience to biodegradation, Rhodamine B is an essential textile colorant in the cotton

sector. The European Food Safety Authority has classified its genotoxic and carcinogenic effects. This means it is illegal in several nations, including the EU and China [134]. It has many practical uses, such as being a dye for tracing in biotechnology, a food colorant, a fluorescent water tracer, and a textile colorant. According to several scientific studies, human and animal health is negatively impacted by RhB. When compared to other colors, it is the most harmful dye that ends up in wastewater. Its low price and vivid reddish-orange color make it useful in many items, including dye lasers, pyrotechnics, ballpoint pens, carbon sheets, paintings, and leather goods [135]. RhB is carcinogenic when inhaled or consumed, irritating the skin and eyes and wreaking havoc on the thyroid and kidneys. The ability of MXene and nanocomposites containing MXene to break down contaminants in water, and how this may help preserve ecosystems vital to human and animal health, is discussed below.

To create ultrathin $\text{Bi}_2\text{WO}_6/\text{Nb}_2\text{CT}_x$ hybrid nanosheets for the photocatalytic degradation of RhB, Cui et al. used a straightforward hydrothermal technique [136]. Several characterization techniques, such as transmission electron microscopy, field emission scanning electron microscopy, X-ray photoelectron spectroscopy, and dynamic light scattering, were used to assess the structural behavior, XRD spectra, zeta potential, and lateral size of Nb_2CT_x , Bi_2WO_6 , and $\text{Bi}_2\text{WO}_6/\text{Nb}_2\text{CT}_x$ nanomaterials. The remarkable thermal, chemical, and photostability of bismuth tungstate makes it an attractive photocatalyst for degrading dyes. Their inefficient photodegradation capability, caused by the slower separation speed of photogenerated electron–hole pairs, greatly limits their use. MXene is advantageous for speeding up the process of separating photogenerated electron–hole pairs. Composite formation with Nb_2CT_x , therefore, alters the photocatalytic characteristics of Bi_2WO_6 . Compared to Bi_2WO_6 , the photodegradation efficiency for RhB was 99.8 percent with the $\text{Bi}_2\text{WO}_6/\text{Nb}_2\text{CT}_x$ photocatalysts. After combining Bi_2WO_6 with 2 wt% Nb_2CT_x for RhB, the photocatalysis constants were determined to be 0.072 min^{-1} . Compared to the photocatalysis constants of pure Bi_2WO_6 , these values were 2.8 and 2 times higher, respectively.

After subjecting 2D Ti_3C_2 MXene to hydrothermal, ion exchange, and calcination treatments in sequence, Tran et al. achieved safflower-shaped $\text{TiO}_2/\text{Ti}_3\text{C}_2$ heterostructures [137]. These heterostructures were subsequently used to photodegrade the synthetic organic dye RhB in water. Nanomaterials based on MXene were shown to have their shape, internal structures, and characteristics significantly affected by thermomechanical factors. Under ideal circumstances, the $\text{TiO}_2/\text{Ti}_3\text{C}_2$ nanocomposites behave as semiconductors, in opposition to $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. After only one hour, the $\text{TiO}_2/\text{Ti}_3\text{C}_2$ composite had broken down RhB at 95%. The generated nanocomposite's outstanding photocatalytic activity could be caused by its porous structure. One metal oxide that shows promise for application in photocatalysis is titanium dioxide. Among its many advantages are its excellent reliability, absence of toxicity, and outstanding performance in carrier processes. Its lower visible region activity and quick charge carrier separation are two of TiO_2 's drawbacks. The remarkable 2D material MXene produced a composite that addresses these difficulties. The structural behavior and morphology of the $\text{TiO}_2/\text{Ti}_3\text{C}_2$ composite have been examined using various characterization techniques, including XRD, BET, TEM, and XPS. Because of its porous safflower structure and the fast carrier production of TiO_2 , the composite outperformed the pure MXene.

Created by mixing $\text{TiO}_2@\text{Ti}_3\text{C}_2$ MXene and $\text{g-C}_3\text{N}_4$ graphene using an ultrasonic-assisted calcination process, a $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ photocatalyst was developed by Ding et al. [122]. They used this photocatalyst to break down RhB in water and wastewater. Various characterization approaches were used to investigate the photoelectrochemical characteristics, elemental composition, and morphological structures of the $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ photocatalyst. These methods included scanning electron microscopy, FTIR, trans-

mission electron microscopy, XRD, and ultraviolet light. Photogenerated electrons and holes may be of a higher quality in the g-C₃N₄ composite if graphene is used. Hybrids of TiO₂@Ti₃C₂/g-C₃N₄ may further benefit from O/OH categories of functional activities on MXene's surface and the resulting TiO₂, which might speed up the electron transport. In only one hour of visible-light exposure, the TiO₂@Ti₃C₂/g-C₃N₄ photocatalyst achieved a rate of about 99.9 percent photodegradation. According to the data, a nanocomposite photocatalyst of TiO₂@Ti₃C₂/g-C₃N₄ outperformed pure g-C₃N₄ by a factor of 1.33. The pristine g-C₃N₄, Ti₃C₂, and TiO₂@Ti₃C₂/g-C₃N₄ samples were each given a specific surface area of 8.658 m².g⁻¹, 9.102 m².g⁻¹, and 6.773 m²/g, respectively, using the Brunauer–Emmett–Teller technique. With TiO₂@Ti₃C₂'s capacity to inhibit the self-aggregation of g-C₃N₄, the resulting compound, TiO₂@Ti₃C₂/g-C₃N₄, had a much higher specific surface area. The improved photodegradation of TiO₂@Ti₃C₂ relative to g-C₃N₄ and Ti₃C₂ is due mainly to its considerable surface area (SSA).

For the goal of photocatalytically destroying RhB in water and wastewater, Thirumal et al. used catalytic chemical vapor deposition technology in 2022 to create a hybrid nanocomposite photocatalyst composed of MXene and carbon nanotubes [138]. Many characterization techniques have helped shed light on the photocatalyst's physiochemical characteristics and internal structure, including Fourier transform infrared spectroscopy, XRD, scanning electron microscopy, and Raman analysis. According to their findings, after 15 min of exposure to UV light, the produced photocatalyst and pure MXene demonstrated 75% and 60% efficiency, respectively. The results showed that compared to pure MXene, the manufactured nanocomposite photocatalyst performed better. This process resulted in a photocatalyst that outperformed the original MXene material regarding its specific surface area, interlayer spacing, and the amount of active surface functional groups. In light of these results, the research team was convinced that the newly developed photocatalyst will soon play a pivotal role in effectively removing organic pollutants during wastewater treatment.

5.2. Anionic Dyes

Extensive research has shown that heterostructures based on MXene significantly enhance the degradation of anionic dyes. Anionic dye research has emphasized characterizing CR and MO dye degradation in great detail. Composites of TiO₂/MXene were synthesized by Chen et al. using an in situ solvothermal method. In 1876, Caro created the first methylene blue dye in England. Methylene blue, or tetramethylthionine chloride, is a chemical compound in the phenothiazine family. Its color changes from a bright blue while it is oxidizing to a colorless leuco-MB when it is reduced. It dissolves in water and organic solvents. The substance was the first to be intentionally produced and used as an antibacterial agent in medical therapy. It was also the first color to be utilized as an antiseptic. MB and its components were widely used in the chemotherapeutic sector before sulfonamides and penicillin were discovered. The development of medications for tumor therapy and for several viral and bacterial infections has relied heavily on MB. For aquatic life and people alike, it has various negative aspects. Industries that release it into wastewater reduce oxygen levels and endanger aquatic life in several ways when this effluent combines with freshwater. There is a severe threat to human health from drinking water polluted with MB. Headache, heavy perspiration, nausea, gastrointestinal distress, minor bladder irritation, vertigo, cramping in the stomach, and the frequent need to urinate are all possible symptoms. To better the lives of both people and aquatic life, let us talk about how MXene-based nanomaterials work in the photodegradation of MB for wastewater and water treatment.

A heterostructure photocatalyst composed of MXene and g-C₃N₄ was synthesized by Nasri et al. in 2022 by the wet impregnation approach [139]. This synthesis was carried out to accomplish effective degradation. Analysis using XRD, HRTEM, SAP, DR-UV-vis, FTIR, FESEM, XPS, and BET were among the characterization techniques used. Using these methods, the authors were able to better understand the photocatalytic properties of the MXene/g-C₃N₄ heterostructure. The nanostructure consisting of 1 weight percent MXene and g-C₃N₄ exhibited the greatest photocatalytic efficiency after three hours of exposure to a 500 W halogen light. The improved photocatalytic activity of the MXene/g-C₃N₄ nanostructure photocatalyst is due, in part, to its increased BET SSA, improved XRD crystallinity nanostructures, and decreased energy bandgaps. In addition, it was shown that the electron e[−] is significant for enhanced photocatalytic activity. The enhancement directly resulted from MXene's critical activities, which delayed the reintegration of photocharged transporters and enhanced photocatalytic activity. Overall, this work supported using MXene as a new option for solar-irradiated wastewater treatment, which might increase charge transfer and segregation and speed up dye degradation.

Furthermore, many surface-active sites are provided by the layered composition of Ti₃C₂ and the peculiar mesoporous structure of TiO₂. Adsorption and initiating surface contact with reactants rely on this characteristic to optimize the total photocatalytic effectiveness. The photocatalytic degradation process is greatly aided in this specific environment by active species like •O₂[−] and •OH[−] radicals. A heterostructure made of BiOCl and Ti₃C₂ was prepared by Lian et al., and it outperformed pure BiOCl in terms of MO degradation efficiency [140]. BiOCl enhances the redox process on the surface, and Ti₃C₂ MXene has a coupling effect that lowers the recombination rate.

Hydrothermal synthesis of one-dimensional molybdenum oxide nanobelts was carried out by Abo-Dief et al. Using ultrasonication, MoO₃/SiO₂/MXene binary and ternary composites were created. Two organic dyes, crystal violet, and methyl orange (MO), were tested for their photocatalytic capabilities using the produced MoO₃/SiO₂ and MoO₃/SiO₂/MXene composites. There was a 48.9% deterioration of MO when MoO₃ nanobelts were used and a 74.4% degradation when MoO₃/SiO₂ was used. At 53.7% and 75.9%, the CV dye was found to degrade. Under visible-light irradiation, the MoO₃/SiO₂/MXene composite achieved removal rates of 94.7% and 97.7% for MO and CV dyes, respectively, demonstrating outstanding photocatalytic activity. For MO dye, the rate constants for MoO₃ nanobelts, MoO₃/SiO₂, and MoO₃/SiO₂/MXene composites were found to be 0.00568 min^{−1}, 0.01156 min^{−1}, and 0.02399 min^{−1}, respectively. For CV dye, the rate constants were 0.00679 min^{−1}, 0.01208 min^{−1}, and 0.02798 min^{−1}, respectively. The most active species during photodegradation were hydroxyl radicals, as shown by a scavenging test that sought to identify the principal photoactive species engaged in photocatalysis (Figure 8) [141]. To improve the reaction, the adsorbed organics are transported to more reactive sites by means of the SiO₂ particles, which operate as an efficient adsorbent medium. Due to their high conductivity, large surface area, and reduced charge recombination rate, 2D MXene nanosheets are ideal for use in applications requiring quick charge transfer. The results show that the combination of MoO₃, SiO₂, and MXene is a good choice for cleaning up wastewater.

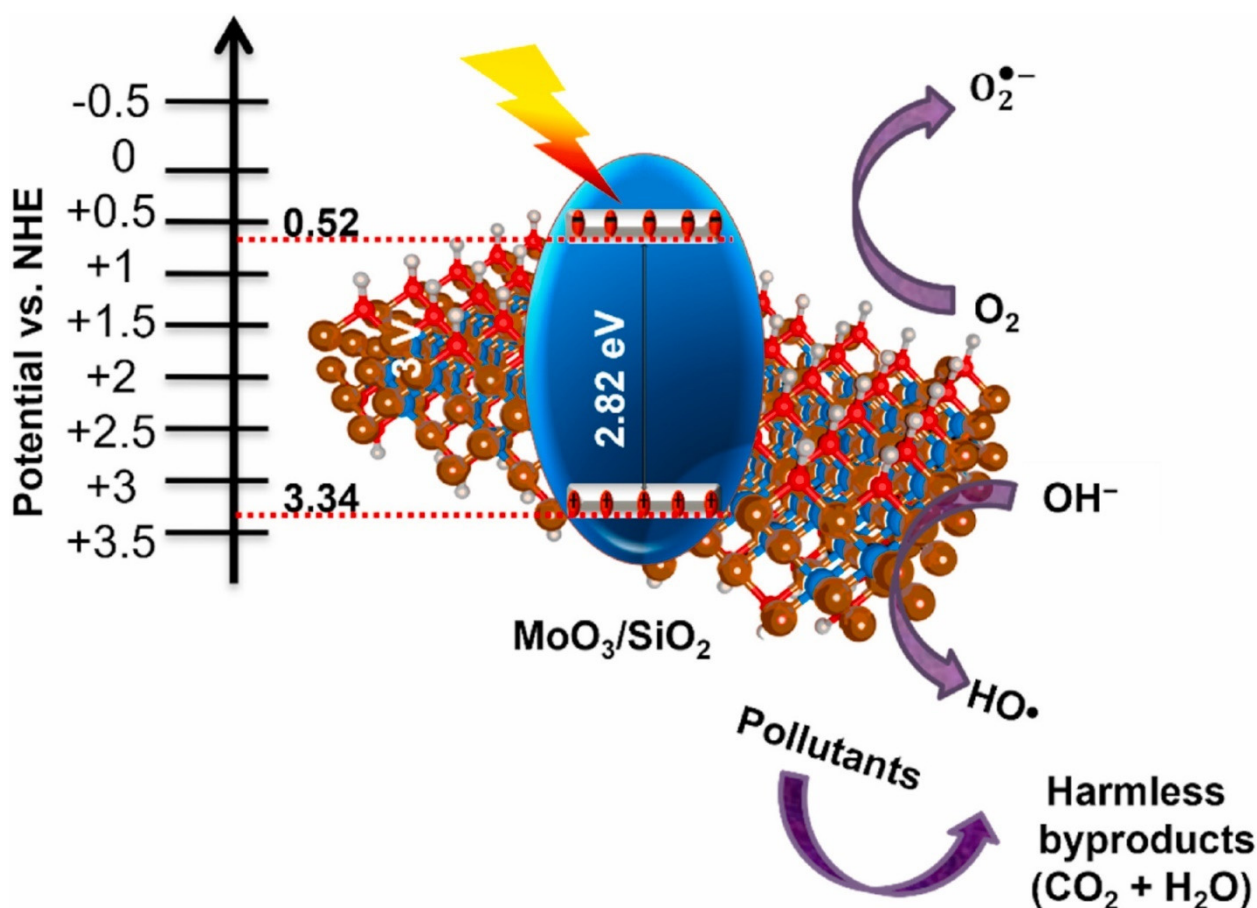


Figure 8. The mechanism of degradation of pollutants by the $\text{MoO}_3/\text{SiO}_2/\text{MXene}$ composite. Reprinted with permission from [141].

5.3. MXene's Photocatalytic Effects in the Removal of Organic Pollutants from Water and Wastewater

Dyeing is a common practice in many different businesses since dyes are potent chemical compounds used to color a variety of goods. Ingredients such as synthetic dyes are in great demand because they are ubiquitous in everyday life. Food processing, pulp and paper, leather, textiles, and cosmetics are just a few of the technical and industrial areas that may benefit from MXene's use. Some of these colors are poisonous and carcinogenic and may irritate the skin and eyes [136,142]. There has been a recent crackdown on some synthetic hues due to mounting evidence that they cause allergic responses and even cancer. Many synthetic dyes are not biodegradable, which means they end up in rivers and on land, where they cause much trouble for the environment. Natural colors from plants, animals, and minerals were widely used before synthetic dyes were invented. Excessive dyes in water reduce the surplus of light needed for optimal photosynthetic processes, which hinders the photosynthetic process. Several two-dimensional nanomaterials have been investigated in the literature in the context of dye photodegradation [143–145]. When oxygen levels in the water drop, aquatic life dies.

By selectively removing the Al layer from the Ti_3AlC_2 parent material, Miao et al. created Ti_3C_2 nanosheets using the HF etching process [146]. After the Ti_3C_2 nanosheets were produced, the next goal was to create a $\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ nanocomposite. A $\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ photocatalyst with exceptional efficiency was synthesized using the in situ solvothermal method. The produced photocatalyst degraded 90% of BPA in 2 h when exposed to a 300 W Hg light. Adding oxygen vacancies and having active hydroxyl radicals and superoxide radicals on the interlayer of the $\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ photocatalyst are the two primary

parameters that significantly impact the degrading performance of the produced photocatalyst. Oxygen vacancies significantly improved the $\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$ material's photocatalytic performance. However, the Schottky barrier was also reduced when OV's were present. Compared to pure TiO_2 and $\text{TiO}_2/\text{Ti}_3\text{C}_2\text{T}_x$, the kinetic constant for BPA degradation was 4.0 times higher with OV's added, while it was 5.5 times higher without. Also, organic vapors (OV's) added to the mix may improve bisphenol A sorption by increasing photocatalytic contact interaction. This research shed fresh light on how to build effective Schottky junction catalysts to remove difficult-to-remove organic contaminants.

For the fabrication of a $\text{TiO}_2/\text{g-C}_3\text{N}_4$ photocatalyst, Wu et al. used the one-step in situ calcination technique in conjunction with MXene Ti_3C_2 [123]. For the visible-light-induced photodegradation of BPA, this photocatalyst was used. The $\text{TiO}_2/\text{g-C}_3\text{N}_4$ photocatalyst was studied using various characterization techniques, such as scanning electron microscopy, transmission electron microscopy, XRD, BET, and XPS. The photocatalyst's morphological structures, chemical composition, and photoelectrochemical characteristics were investigated using these methods. The $\text{TiO}_2/\text{g-C}_3\text{N}_4$ photocatalyst degraded BPA with an efficiency of 79.5% after 50 min of exposure to 300 W Xenon light. The $\text{TiO}_2/\text{g-C}_3\text{N}_4$ photocatalyst successfully removed 63.6% of the BPA in its irradiation experiment. The newly created $\text{TiO}_2/\text{g-C}_3\text{N}_4$ photocatalyst outperformed graphene, pristine TiO_2 , and $\text{g-C}_3\text{N}_4$ in terms of PBA photodegradation efficiency [147]. The photocatalyst based on MXene had a pore volume of $0.135 \text{ cm}^3.\text{g}^{-1}$ and a surface area of $26.41 \text{ m}^2.\text{g}^{-1}$, which were the reasons for its exceptional performance. Furthermore, the photocatalyst had various functional groups that attach to the surface, which made the photodegradation reaction of $\text{TiO}_2/\text{g-C}_3\text{N}_4$ much easier. New photon-capturing regions will form as the pores enlarge in both volume and surface area.

German scientist Otto Unverdorben, who was born in 1806 and passed away in 1873, was the first to synthesize aniline in 1826 by thermally decomposing indigo. Damage to blood and nerve cells, cancer of the blood, cyanosis, and hypoxia are only a few of the severe health problems that aniline dye may cause in people. Because of its negative impact on ecosystems and human health, aniline must be removed from industrial effluents using physical, chemical, and biological methods [148,149]. In this study, the authors go into the complex method of photocatalytic aniline degradation in industrial wastewater.

Created by mixing $\text{TiO}_2@\text{Ti}_3\text{C}_2$ MXene and $\text{g-C}_3\text{N}_4$ graphene using an ultrasonic-assisted calcination technique, a $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ photocatalyst was developed by Ding et al. [122]. Water and wastewater are ideal environments for this photocatalyst to break down aniline. Various characterization approaches were used to investigate the photoelectrochemical characteristics, elemental composition, and morphological structures of the $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ photocatalyst. These methods included scanning electron microscopy, transmission electron microscopy, XRD, FTIR, and XPS. Graphene, a component of the composite material $\text{g-C}_3\text{N}_4$, is an excellent electron and hole generator. Hybrids of $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ may work better if the surface of MXene and the by-product TiO_2 include active O/OH functional groups that allow electrons to flow through them. Aniline is an organic dye, and the $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ photocatalyst showed remarkable degradation capabilities under visible light. It degraded the dye at around 76.4% during 8 h. These findings indicate a five times higher photocatalytic performance than pure $\text{g-C}_3\text{N}_4$ for the $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ nanocomposite. Using the Brunauer–Emmett–Teller method, the specific surface areas of virgin $\text{g-C}_3\text{N}_4$, Ti_3C_2 , and $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ were found to be $8.658 \text{ m}^2/\text{g}$, $6.773 \text{ m}^2.\text{g}^{-1}$, and $9.102 \text{ m}^2.\text{g}^{-1}$, respectively. Since the $\text{TiO}_2@\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ material inhibits the $\text{g-C}_3\text{N}_4$ from self-aggregating, its specific surface area is much greater. One important factor that makes $\text{TiO}_2@\text{Ti}_3\text{C}_2$ photodegradation better than $\text{g-C}_3\text{N}_4$ and Ti_3C_2 is its substantial surface area (SSA). Also, to enhance electron transport and photocat-

alytic performance, the researchers recommended creating an n-type Schottky heterostructure and an n-type junction between the surfaces of the $\text{TiO}_2/\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ photocatalyst. In conclusion, the study proved that the environmentally friendly $\text{TiO}_2/\text{Ti}_3\text{C}_2/\text{g-C}_3\text{N}_4$ is an attractive option for breaking down organic contaminants.

Zhou et al. developed a unique $\text{Cu}_2\text{O}/\text{Cu@MXene}$ composite with a nanoconfinement structure, which efficiently activates peroxydisulfate to generate hydroxyl radicals for the degradation of tetracycline (TC) (Figure 9a). The results showed that the amazing multilayer structure and surface negativity of MXene might prevent the aggregation of $\text{Cu}_2\text{O}/\text{Cu}$ nanoparticles by immobilizing them within the interlayer spaces. As shown in Figure 9b, the TC removal efficiencies for $\text{Cu}_2\text{O}/\text{Cu}$ were 17.3%, for PMS alone, 25.74%, and for MXene they were 30.18%. Figure 9c shows that the CM-3 performed better than the others when removing TC. Figure 9d also shows the results of modeling the TC degradation kinetics using the pseudo-first-order equation. For TC elimination with $\text{Cu}_2\text{O}/\text{Cu}$, CM-4, CM-3, CM-2, and CM-1, the corresponding pseudo-first-order reaction kinetic constants were 0.0467, 0.0615, 0.0944, 0.1505, and 0.1432 min^{-1} , respectively. The low selectivity of the key active species OH in the CM-3 system towards intermediates is mainly responsible for the 35.3% total organic carbon elimination of tetracycline after 30 min, as shown in Figure 9e. Additionally, two separate degradation pathways were postulated using the degradation intermediates detected by LC-MS. (Figure 9f) [150]. This work offers a novel reference for mitigating nanoparticle aggregation and expands the use of MXene materials in environmental cleanup.

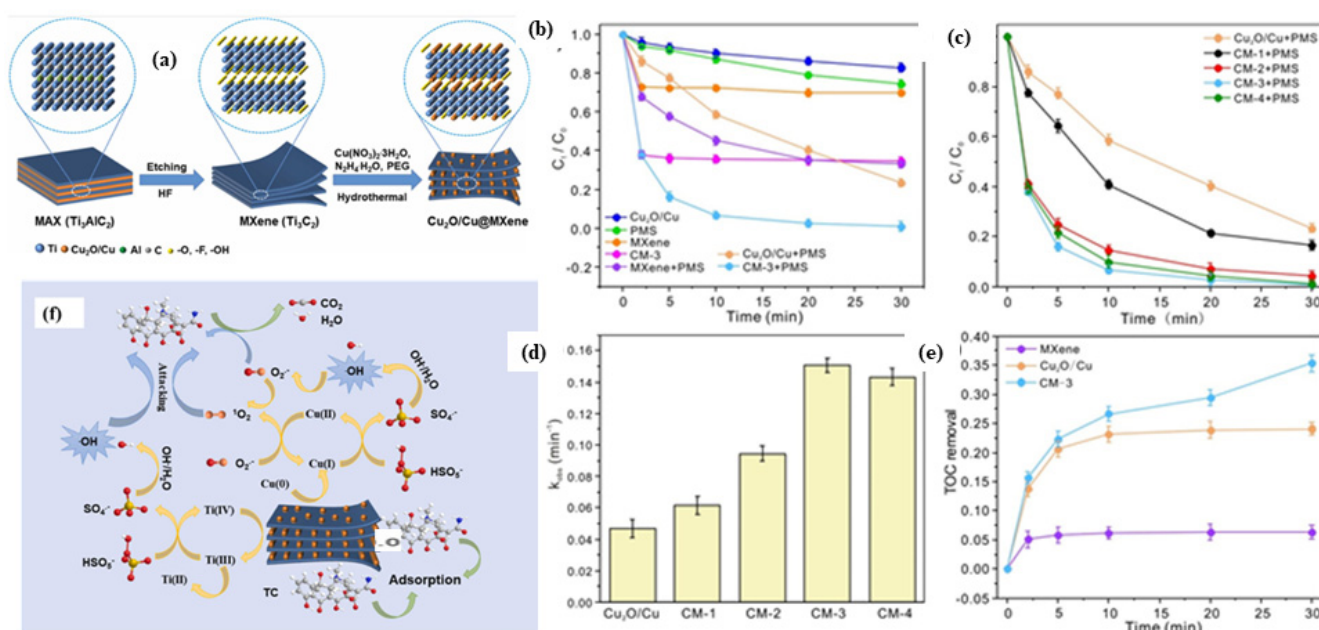


Figure 9. (a) Synthesis scheme of prepared material; (b) TC degradation in various reaction conditions; (c) removal efficacy and (d) pseudo-first-order rate constants; (e) TOC reduction in TC; (f) mechanism of action of prepared material. Reprinted with permission from [150].

Zhang et al. prepared a Ti_3C_2 -reinforced $\text{g-C}_3\text{N}_4$ heterojunction material (MX/CN) via solvent drying (Figure 10). Under visible light irradiation, MX/CN showed improved photocatalytic activity against CIP, thanks to the higher electron transfer rate achieved by the heterojunction composite. With a CIP photocatalytic removal rate of 97.8%, the MX/CN sample outperformed the CN sample by a factor of 1.23. Additionally, at a pH of 7 and an initial CIP concentration of 10 mg/L, 6-MX/CN demonstrated the most photocatalytic activity. A drop in CIP degradation efficiency to 30.9% was caused by the introduction of HCO_3^{3-} , which induced a competitive redox reaction with $\cdot\text{OH}$ in the system and inhibited

the degradation of CIP under neutral circumstances. The presence of Cl^- and NO_3^- also had no effect. Through active species trapping assays, the photocatalytic degradation of CIP by MX/CN was shown to be primarily mediated by $\cdot\text{O}_2^-$, with substantial contributions from h^+ and $\cdot\text{OH}$. After five cycles, the MX/CN cycling trials demonstrated a CIP degradation efficiency of more than 90% [151].

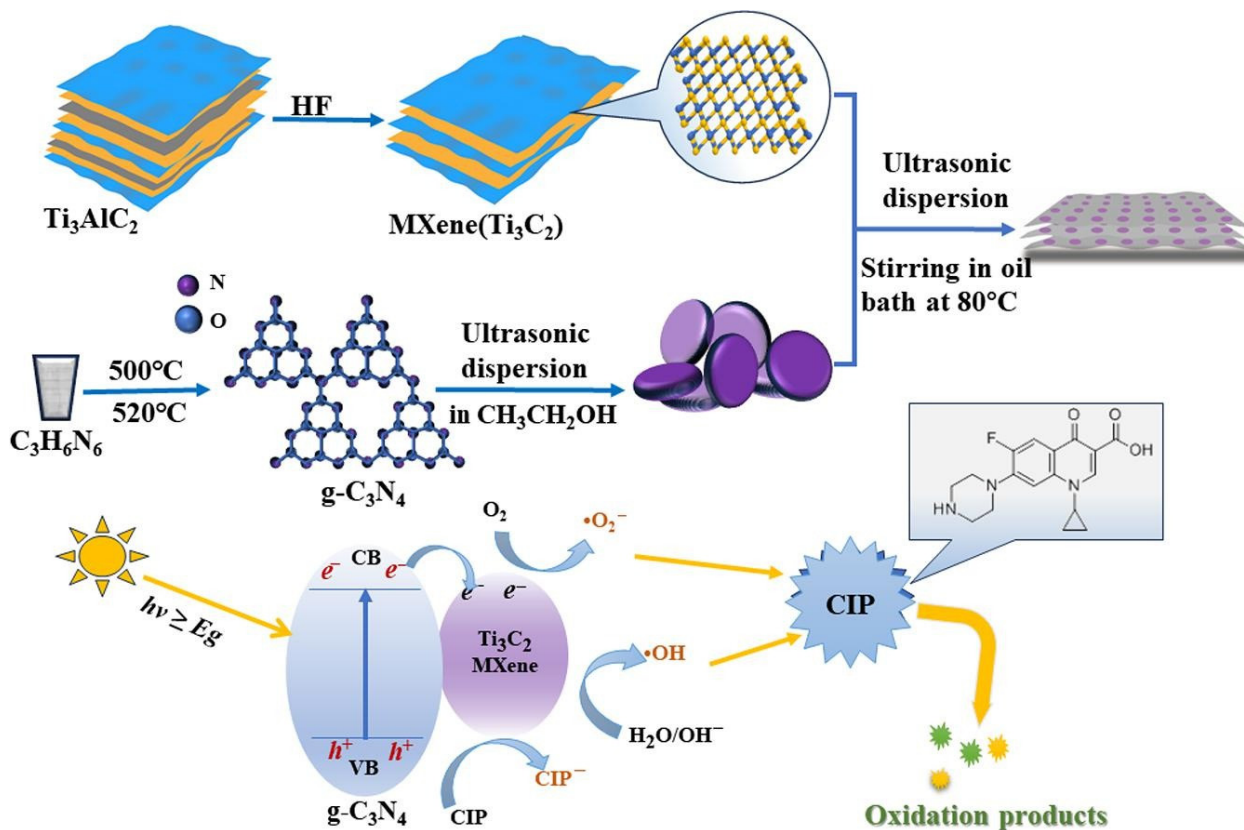


Figure 10. Mechanism of degradation of pollutant degradation. Reprinted with permission from [151].

5.4. Heavy Metal Pollutant Degradation

Heavy metals are an elemental category with various chemical and biological effects. Heavy metals are considered environmental poisons because of the damage they do to plants, animals, and humans. Both natural and human activity cause the heavy metal pollution of soil. The amounts of heavy metals on land have been dangerously elevated due to human activities, including farming, mining, and casting. Heavy metals accumulate in plants and soil due to their innate persistence [152]. Toxic metals interfere with plant growth, dry matter accumulation, and production by interfering with physiological processes such as gaseous exchange, nutrient absorption, and photosynthesis. Using a one-step hydrothermal method, Zhao et al. created a $\text{Bi}_2\text{MoO}_6/\text{Ti}_3\text{C}_2$ -based nanocomposite on MXene [153]. This synthesis produced a photocatalytic material that might break down Cr^{+6} pollutants, typical in water and wastewater, into less toxic forms. By using various characterization methods such as XRD, TEM, SEM, EDS, HRTEM, BET, PL, EIS, EPR, and DRS, the exceptional photocatalytic activity of the $\text{Bi}_2\text{MoO}_6/\text{Ti}_3\text{C}_2$ nanocomposite in pure Bi_2MoO_6 was illuminated. After 60 min of exposure to visible light, the photocatalyst made of synthetic MXene demonstrated complete photodegradation activity. Research shows that compared to pure Bi_2MoO_6 , the photodegradation efficiency of the $\text{Bi}_2\text{MoO}_6/\text{Ti}_3\text{C}_2$ photocatalyst is 11.2 times higher. This research opens up new possibilities for studying efficient and cost-effective photocatalysts.

A novel MXene-based photocatalyst was created in research by Sun et al. in 2021 using the electrostatic self-assembly method [154]. Water and wastewater containing inorganic contaminants, such as Cr^{+6} , may be effectively degraded by this photocatalyst. Under visible light for 60 min, the photocatalyst based on MXene could photodegrade 61% of the sample. Compared to pure Ag_3PO_4 , the photocatalyst's test results showed a 1.46-fold boost. In addition, the photocatalyst's efficiency in degrading Cr^{+6} e-active species was reduced by as much as 29.8 percent when AgNO_3 was used instead of Ag_3PO_4 . When Cr^{+6} is present, the photodegradation of inorganic contaminants may be controlled. The method for building a MXene photocatalyst for wastewater treatment is detailed in the aforementioned scientific article and is very successful.

Yu et al. applied Ag nanoparticles onto $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, resulting in a novel photocatalyst dubbed MXene-based $\text{Ag}/\text{Ti}_3\text{C}_2\text{T}_x-\text{O}$ [154,155]. This photocatalyst was engineered to break down uranium (U^{+6}) in wastewater and water for ecological reasons. Composites based on MXene were thoroughly characterized using various methods to understand their physicochemical behavior. The photocatalyst based on MXene degraded U^{+6} in wastewater after 2 h when exposed to light, with a photocatalytic activity of $1257.6 \text{ mg}\cdot\text{g}^{-1}$. This activity was almost eleven times higher compared to what would be seen in complete darkness. This research sheds light on the process of U^{+6} amplification and offers a way forward for creating effective catalysts for the photocatalytic degradation of U^{+6} .

To reduce U^{+6} from a water-based solution via photocatalysis, Li et al. developed $\text{g-C}_3\text{N}_4/\text{Ti}_3\text{C}_2$ MXene [156]. Their study found that compared to pure carbon nitride (CN) and Ti_3C_2 MXene the CN/TC-2 photocatalyst degraded U^{+6} from water more effectively. The adsorption selectivity for U^{+6} was significantly improved when Ti_3C_2 was added to CN. Under both dark and light illumination circumstances, the researchers tested the photodegradation effectiveness of the newly synthesized photocatalysts. However, compared to when it was in the dark, the photodegradation activity of U^{+6} was drastically changed when exposed to light. With a rate constant of 0.267 min^{-1} , TC/CN-2 demonstrated the highest efficiency for U^{+6} among the photocatalytic removal procedures. The rate constant of CN is 0.019 min^{-1} , while this value is 14.05 times higher. According to researchers, cocatalysts added to materials like MXenes and TiO_2 may increase catalyst photoactivity for U^{+6} degradation.

Another work effectively synthesized MIL-88A(Fe)/MXene Type-I heterojunction photocatalysts. The active crystal plane of MIL-88A(Fe) was altered by adjusting the solvent ratio in the solvent-thermal process (Figure 11a). The study focused on sulfamethoxazole as the primary pollutant, examining the impact of various MIL-88A(Fe) morphologies and differing MXene loadings on the photocatalytic efficacy of the composite. The findings indicated that the degradation rate of sulfamethoxazole by DA-M100 composite photocatalysis, in conjunction with the Fenton effect, achieved around 70% after 10 min of light exposure, with a degradation efficiency of 92.66% after 60 min of light exposure. The universality test demonstrated that DA-M100 exhibited effective photo-Fenton oxidation capabilities for prevalent dyes and proficient photo-Fenton reduction abilities for heavy metal ions in wastewater. After one hour of irradiation, the removal efficiencies of Cr (VI), Cu (II), and Ni (II) were 95.88%, 79.77%, and 66.67%, respectively (Figure 11b) [157]. The stability trials demonstrated that DA-M100 exhibited strong environmental adaptability. The findings indicate that the iron-based MOF and MXene complex has significant potential for industrial wastewater treatment and offers a novel approach for altering Type-I heterojunctions.

Table 2. Comparison of various MXene-based nanocomposites for pollutant removal.

Photocatalyst	Method	Dosage	Light Source	Pollutant	Conc.	Removal Efficiency (%)	Duration (h)/ Temperature (K)	Ref.
MXene/TiO ₂ /g – C ₃ N ₄	Calcination	60	300 W xenon lamp	BPA	5.0	70.1	1.16/298	[123]
Ag/Ag ₃ PO ₄ /Ti ₃ C ₂	Electrostatic self-assembly technique	50	300 W Xe arc lamp	Cr6+	20	61.0	1.0/298	[154]
TiO ₂ /g–C ₃ N ₄ /Ti ₃ C ₂	CVD and calcination	-	300 W xenon lamp with a filter (>420 nm)	TC-HCl	10.0	96.05	1.5/298	[159]
Ag/Ti ₃ C ₂ T _x -O	Depositing	10	Visible light	U+6	100	1257.6 mg/g	2.0/298	[155]
MXene/TiO ₂ /g – C ₃ N ₄	Calcination	60	300 W xenon lamp	RhB	20	97.6	0.5/298	[123]
BGFO-20Sn/MXene	Coprecipitation method	100	300 W xenon lamp	CR	10	100	2.0/298	[160]
Bi ₂ MoO ₆ /Ti ₃ C ₂	One-step hydrothermal method	-	50 W white LED	Cr+6	15	100	1.0/298	[153]
Ti ₃ C ₂ T _x /Ti ₃ AlC ₂ @Ag	Reduction process	1000	300 W UV lamp	MO RhB	10	99.3	0.5/298	[161]
TiO ₂ /Ti ₃ C ₂ T _x	In situ solvothermal	5.0	300 W Hg lamp	BPA	15	90.5	2.0/298	[146]
C ₃ N ₄ /Ti ₃ C ₂ -AgNPs	Photo deposition reduction	-	UV irradiation	Aniline	-	81.8	8.0/298	[162]
g-C ₃ N ₄ /Ti ₃ C ₂	Heat polymerization	0.6	500 W Xe lamp	U+6	0.1 mM	0.267 min ^{−1}	1.3/298	[156]
TiO ₂ /g–C ₃ N ₄	Calcination	60	300 W xenon lamp	CP BPA	20	83.5 79.5	1.33/298	[123]
BLFO/Ti ₃ C ₂	Double solvent sol–gel method	100	Dark conditions	CR	10	92	1.3/298	[163]

Table 2. Cont.

Photocatalyst	Method	Dosage	Light Source	Pollutant	Conc.	Removal Efficiency (%)	Duration (h)/ Temperature (K)	Ref.
TiO ₂ /Ti ₃ C ₂ T _x heterojunction	In situ solvothermal method	50	500 W mercury light	MB	1.0	97.8	0.5/298	[164]
Ti ₃ C ₂ T _x -CNTs	Catalytic chemical vapor deposition	100	UV	RhB	0.01	75	0.25/298	[138]
TiO ₂ /Ti ₃ C ₂ T _x	In situ solvothermal	50	500 W Hg lamp	MO	10	90.5	1.15/298	[165]
Bi ₂ WO ₆ /Nb ₂ CT _x	Hydrothermal	50	500 W Xe lamp	MB	15	92.7	0.2/298	[136]
Ti ³ C ₂ /TiO ₂ composite	Hydrothermal	35	Solar irradiation	RhB	30	96	0.6/298	[166]
C-TiO ₂ /Bi ₄ NbO ₈ Cl	Calcination	40	300 W Xenon lamp	MO	10	49	3.0/298	[167]
BFO/Ti ³ C ₂	Double solvent solvothermal method	100	300 W xenon lamp	CR	30	100	2.0/298	[168]
AgNPs/TiO ₂ /Ti ₃ C ₂ T _x	Hydrothermal	10	Simulated solar light	MB	10	96	2.0/298	[169]
AgNPs/TiO ₂ /Ti ₃ C ₂ T _x	Hydrothermal	10	400 W Hg lamp (UV)	RhB	10	99	0.6/298	[169]
BPQDs/Ti ₃ C ₂ @TiO ₂	Hydrothermal	50	Visible-light irradiation ($\lambda \geq 420$ nm)	MO	10	93	1.0/298	[170]
MXene/g-C ₃ N ₄	Wet impregnation method	500	500 W halogen lamp	MB	10	69.4	3.0/298	[139]
Ti ₃ C ₂ T _x @Sb-H	Simple hand grinding method	100	125 W- 365 nm lamps	MB	1.0	82	1.3/298	[171]
BiVO ₄ /Ti ₃ C ₂ heterojunction composite	Ultrasonicated Treatment	100	300 W xenon lamp	MO CR	10	99.1 99.5	2.16/298	[172]
TiO ₂ /Ti ₃ C ₂	Hydrothermal	20	300 W xenon lamp	RhB	20	93	1.0/298	[173]
handmade MXene (Ti ₃ C ₂) MX-H	Kitchen blender technique	2.0	300 W visible light	MB	-	98	0.5/298	[174]

Table 2. Cont.

Photocatalyst	Method	Dosage	Light Source	Pollutant	Conc.	Removal Efficiency (%)	Duration (h)/ Temperature (K)	Ref.
Potassium Poly(heptazine imide)/Ti ₃ C ₂ MXene	In situ synthesis	10	Visible light	Rhodamine 6G	20	96.3%	1h/298	[175]
BiVO ₄ /MXene	Hydrothermal synthesis	15	Visible light	Cr(VI)	10	96.39%	2h/298	[176]
Ti ₃ C ₂ @TiO ₂	Reflux method	20	Visible light	Tetracycline	15	90%	1.5h/298	[177]
Ba _{1.9} Ho _{0.1} Sr _{1.5} Ni _{0.5} Fe ₁₂ O ₂₂ @MXene	Ultrasonication method	-	Visible light	Rhodamine B	10	78.88%	2.3h/298	[178]
Ti ₃ C ₂ -MXene/NiO	Hydrothermal method	25	UV light	Crystal Violet (CV)	-	92.8%	1.5h/298	[179]
BiOBr/Ti ₃ C ₂ MXene	Hydrothermal method	30	Visible light	Rhodamine B	20	99.9%	1h/298	[180]
Cu ₂ O/BiVO ₄	Chemical synthesis	50	Visible light	Methylene Blue (MB)	30	97%	2h/298	[181]
MXene/Bi ₂ O ₃ -V ₂ C	Hydrothermal synthesis	10	Visible light	NO	50	94%	2h/298	[182]
Ag ₂ MoO ₄ /ZnWO ₄	Z-scheme construction	20	Simulated sunlight	Methylene Blue (MB)	20	99.8%	1h/298	[183]
Bi ₂ O ₂ CO ₃ @MXene	In situ method	-	Visible light	Rhodamine B	10	98.4%	5h/298	[184]

6. Other Applications of MXene-Based Photocatalysts

6.1. Hydrogen Evolution by Photocatalytic Water Splitting

MXenes have significant water stability and possess a hydrophilic surface, making them highly conductive metals [185]. The improved photocatalytic hydrogen evolution reaction of MXene results from its inherent catalytic activity. The performance of semiconductor is enhanced by the Schottky barrier that can develop between the MXene and the semiconductor, facilitating electron pooling and reducing charge recombination inside the semiconductor's band structure. ^{-}O or ^{-}OH functional groups are the most preferred in M_2XT_x -type MXene. When T_x is a ^{-}F species, the hydrogen evolution reaction (HER) activity of MXene is markedly diminished. Alterations in the species composition of T_x lead to substantial variations in HER overpotential and MXene activity. As the loading of MXenes with other chemicals increases, the likelihood of achieving a better hydrogen evolution reaction (HER) diminishes [186]. Surface functionalization may be adjusted by replacing certain moieties with varying hydrogen adsorption strengths, such as ^{-}O or ^{-}OH in place of the ^{-}F group. The delamination of the MXene interlayers enhances the availability of the basal plane for hydrogen evolution reaction (HER) activity. Modifying the shape and enhancing interfacial coupling may facilitate a reduction in Schottky barrier contact and the augmentation of hydrogen evolution reaction (HER) activity [100,187]. The energy of metal d-states and surface reactivity are both augmented when structural strain is exerted on monolayer MXene [188,189].

The T_x surface functional groups on MXenes demonstrate effective hydrogen evolution reaction catalysis by improving hydrogen contact, generating more active sites, and enlarging the reaction zone. Ni_2P has significant activity, stability, and superior conductivity, resulting in noteworthy oxygen evolution reaction (OER) performance, as shown by research findings [72]. To assess the potential of their $\text{Ni}_2\text{P}/\text{Cr}_2\text{CO}_2$ (MXene) composite as an efficient bifunctional catalyst for overall water splitting (OWS), Y Cheng et al. performed functional theory investigations [72]. A novel $\text{Ti}_3\text{C}_2/\text{TiO}_2/\text{MoS}_2$ composite, presented by Yujie Li and associates, showed a significant enhancement in photocatalytic hydrogen evolution reaction (HER) performance because of its remarkable stability under reaction circumstances, achieved by heterojunction formation via the co-exposed (101) and (001) facets. The photocatalytic process may achieve an effective interfacial charge transfer due to the large contact area between the cocatalyst and photocatalyst, resulting in the greatest H_2 evolution rate of $6425.29 \mu\text{mol h}^{-1} \text{g}^{-1}$ [190].

Researchers were able to create 2D/2D MXene/CdS composite catalysts that showed an improvement in NIR photoresponse. Photocatalytic hydrogen evolution using near-infrared light irradiation employs in situ-produced composite catalysts composed of CdS nanosheets atop $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets. The hydrogen evolution rate of the ideal CM3 catalyst is $27.4 \text{ mmol g}^{-1} \text{h}^{-1}$, which is 4.2 times more than that of the pure CdS catalyst and the Pt/CdS photocatalyst. It is possible that three factors contribute to the efficient production of hydrogen from 2D/2D MXene/CdS: (i) the photothermal effect can be started and the photochemical reaction accelerated by using MXene's photoabsorption and strong near-infrared (NIR) light response; (ii) as an electron capture medium and hydrogen evolution cocatalyst, MXene helps to quickly separate photogenerated carriers; and (iii) when CdS is combined with 2D MXene, the reaction's electrons travel a shorter distance, which reduces the chance of carrier recombination. Future research on merging photothermal effects with MXene for photocatalytic hydrogen production may use this work as a reference; it also provides a new way of looking at the problem of making photocatalytic hydrogen-generating applications more scalable [191].

6.2. CO₂ Reduction

An exciting new field of research, photocatalytic carbon reduction employs a catalyst and sunlight to produce useful compounds and fuels from carbon dioxide (CO₂). Solar radiation excites electrons across catalyst surface sites, setting in motion chemical processes that transform CO₂ into other compounds [192]. A green and long-term solution to climate change and the need for renewable energy may be possible with this. Each of the several varieties of photocatalysts has its own set of pros and cons. Titanium dioxide (TiO₂) and other metal oxides and semiconductors are among the most prevalent types of photocatalysts [193]. The target product and operational circumstances dictate the photocatalyst selection [194].

Zhong et al. (2023) assert that enhanced heterojunction interfaces in photocatalyst systems may be developed by integrating semiconductors with MXenes, characterized by their lamellar structure and unique surface rich in terminations. This amalgamation accelerates charge separation and transfer, resulting in improved photocatalytic activity [195]. A ZnO/Ti₃C₂ photocatalyst with a 1D/2D heterojunction interface was produced by electrostatic self-assembly, demonstrating efficacy as a CO₂ photocatalyst [196]. The optimized sample containing 7.5 wt% Ti₃C₂ exhibited a substantial enhancement in CO₂ photoreduction, achieving CH₄ and CO yields of 20.33 and 30.30 $\mu\text{mol g}^{-1} \text{ h}^{-1}$, respectively. These values are 35 and 7 times greater than those reported for ZnO, respectively. The use of Ti₃C₂ as a cocatalyst facilitates the activation of adsorbed CO₂ and improves charge separation and transfer.

Yang and colleagues synthesized a 2D/2D heterojunction photocomposite of ultrathin Ti₃C₂/g-C₃N₄ by directly calcinating Ti₃C₂ MXene and urea [197]. The optimal sample surpassed pure g-C₃N₄ by a factor of 8.1 in CH₄ and CO yields (0.044 $\mu\text{mol g}^{-1} \text{ h}^{-1}$ and 5.19 $\mu\text{mol g}^{-1} \text{ h}^{-1}$, respectively). The establishment of a 2D/2D intimate heterojunction between g-C₃N₄ and Ti₃C₂ enhances the effective separation of charge carriers generated by light, resulting in this enhancement. As a result, the lifetime of the charge carriers was extended, while their recombination was eliminated. Two further instances of 2D/2D heterojunction systems using MXene, which demonstrate effective catalytic reduction reactions (CRR), are 2D/2D Ti₃C₂ MXene/g-C₃N₄ [198] and 2D/2D V₂C/porous g-C₃N₄ [199].

Photocatalytic hydrogen evolution reaction (HER) has used many meticulously engineered heterojunction photocatalysts. An ultrathin delaminated Ti₃C₂ nanosheet surface facilitated the synthesis of one-dimensional CdS nanorods, then used to fabricate a one-dimensional/two-dimensional CdS/Ti₃C₂ nanocomposite [200]. The expansion enabled the CdS nanorods and Ti₃C₂ nanosheets to achieve optimal contact, hence promoting rapid and efficient charge transfer. The ideal sample with 20 mg of MXene cocatalyst demonstrated exceptional photocatalytic hydrogen evolution reaction (HER) performance under visible light, attaining a peak hydrogen generation rate of 2407 $\mu\text{mol g}^{-1} \text{ h}^{-1}$, which represents a seven-fold enhancement relative to CdS nanorods. The Ti₃C₂ cocatalyst demonstrates enhanced photoactivity due to its well-engineered contact interface, superior conductivity, and unique two-dimensional morphology. Sun et al. have recently developed an efficient and stable 1D/2D CuZnInS/Ti₃C₂ photocatalyst for hydrogen generation. The enhanced sample surpasses CuZnInS by a factor of 4.5, exhibiting a HER rate of 15.24 $\text{mmol h}^{-1} \text{ g}^{-1}$. This improvement results from the efficient suppression of charge carrier recombination facilitated by the presence of MXene [201].

7. Conclusions

MXenes have demonstrated significant potential as advanced materials in photocatalysis, primarily due to their unique physicochemical properties, such as high electrical conductivity, tunable surface functionalities, and exceptional ability to absorb light. The

layered structure of MXenes allows for a high surface area and accommodates active sites, which facilitates the photocatalytic degradation of pollutants. The combination of MXenes with other semiconductors through heterostructure formation has proven to be particularly effective in improving charge separation, lowering recombination rates, and enhancing overall photocatalytic efficiency. Despite their advantages, challenges such as oxidation susceptibility, limited scalability, and material restacking remain to be addressed. By optimizing surface modifications and developing composite materials, MXenes can be tailored for more efficient visible-light-driven photocatalysis, offering significant potential in environmental remediation applications.

1. **Advanced Functionalization:** Future studies should focus on optimizing surface terminations ($-OH$, $-O$, $-F$) to enhance photocatalytic activity. Research into non-traditional functional groups and their effects on charge dynamics could open new possibilities for improving MXene performance.

2. **Composite Engineering:** The formation of MXene-based composite materials with semiconductors (e.g., TiO_2 , $g-C_3N_4$) holds promise for enhanced photocatalytic performance. Developing novel hybrid systems and investigating the interplay between MXene layers and other nanostructures will be key to maximizing light absorption and charge separation efficiency.

3. **Environmental Applications Beyond Pollutant Degradation:** While MXenes have shown great promise in degrading organic pollutants, future applications could explore broader areas, such as photocatalytic water splitting for hydrogen production and CO_2 reduction. Expanding the application scope of MXenes could lead to significant advancements in clean energy technologies.

4. **Overcoming Material Limitations:** Addressing the stability issues of MXenes, particularly their tendency to oxidize and restack, will be critical for their large-scale industrial deployment. Developing more robust synthesis techniques, such as fluoride-free etching methods, and coating strategies to prevent degradation will be essential for long-term use in photocatalytic systems.

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