

REVIEW

Exploring the Potential of MXenes for Biomedical and Environmental Applications—An Abridged Review

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ABSTRACT

A new class of 2D nanomaterials called MXenes, which have been of interest in recent years, which possess outstanding electrochemical, biological, optical, and mechanical capabilities. The MXene heterostructures' prominence in technologies including bioimaging, contrast enhancement through luminescence, biosensors, batteries, and environmental applications have picked up pace. This review will cover various intriguing MXene-based biomedical and environmental applications through their most recent developments, design principles, and operational mechanisms. Different forms of MXenes may be associated with pharmaceutical compounds, metallic nanostructured materials, polymeric structures, and other functional components. MXenes face several further advancements as well as significant hurdles in employing them in a right sort of material composition. A thorough discussion of this remarkable material's potential applications and difficulties as discussed in this review along with the highly tunable physiochemical properties.

1 | Introduction

Two-dimensional (2D) materials such as metal organic frameworks, MXenes, and graphene/graphene-based nanocomposites have gained growing interest due to their distinct physicochemical properties; perhaps, graphene and graphene-based nanocomposites serve as future energy technologies, although MXenes are also quite desirable in this situation, extremely secure, and displaying enormous excellent interlayer spacing, atmospheric adaptability, and biocompatibility. In the fields of producing energy, catalysts, environmental engineering, and water/wastewater remediation, many nanomaterials have found a variety of uses. For instance, heavy metals and organic pollutants from

water and wastewater may be absorbed by graphene. Inorganic-organic hybrid composites, also known as metal-organic frameworks, are now often employed as adsorbent materials to remove both inorganic and organic pollutants. However, due to their unique physicochemical features, MXenes could perform better in certain situations, such as large interfacial area, superior oxidation, great durability, and a high melting temperature. Exceptional electrical/thermal conductivity, resistance, and hydrophilicity have seen MXenes and materials based on MXene serving as cutting-edge adsorbents and next-generation membranes, eliminating pollutants from the environment [1, 2]. The synthesis history of 2D MXenes is shown in a representative image from Alhaben et al.'s work in Figure 1 [3].

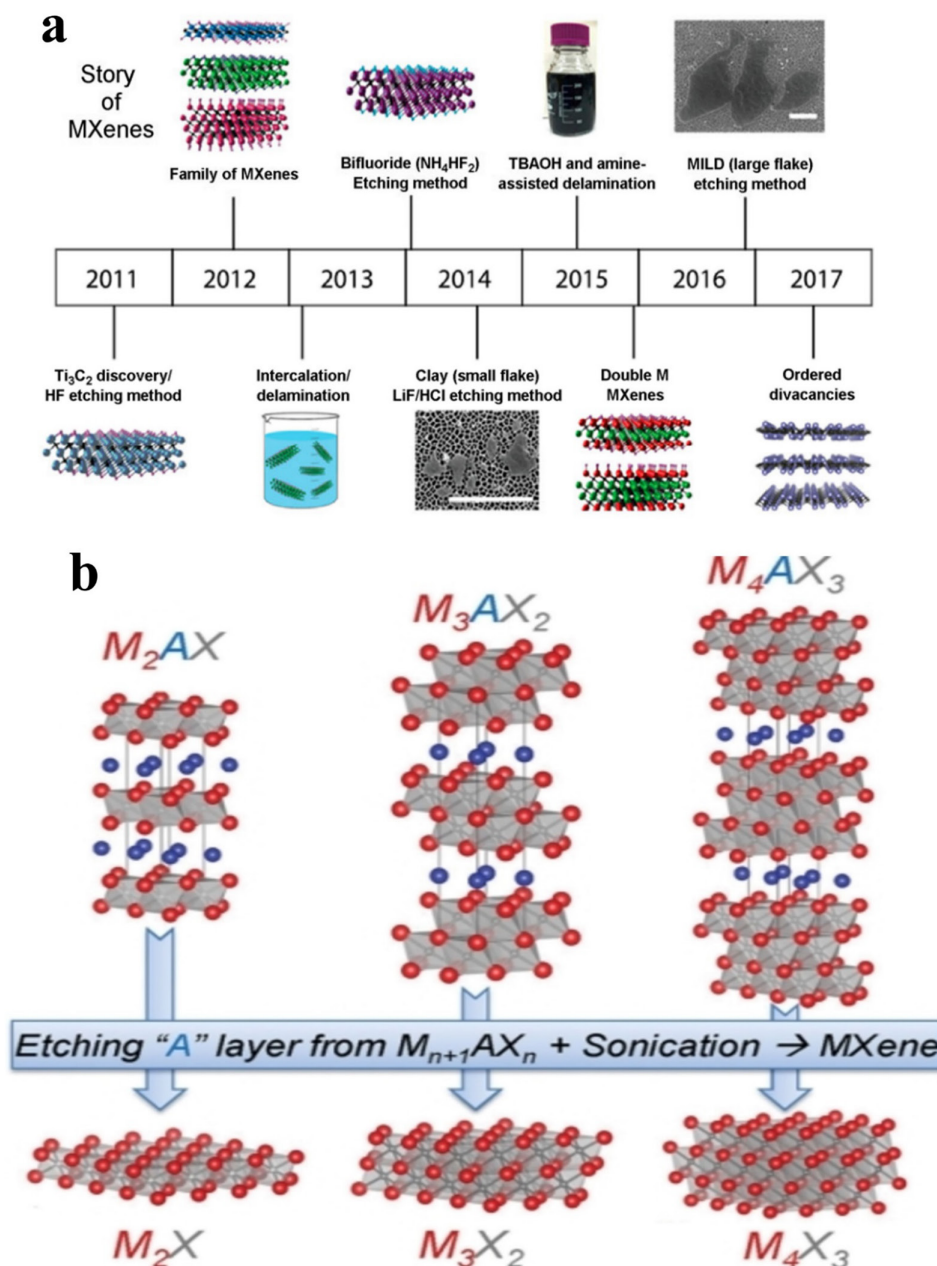


FIGURE 1 | (a) Emergence of MXenes fabrication over the years and (b) schematic of different structural phases of MXenes [3].

Ecological and energy-related challenges are now grabbing the world's attention. Both stationary batteries and electric cars need powerful energy converting and storage systems. There is still a need for more studies and advancements even though current energy conversion/storage technologies, like water splitting, accumulators, and supercapacitors, have made considerable strides. This is because it is difficult to simultaneously achieve high energy transformation and specific power, and rechargeable battery devices are expensive and have a limited range of uses. 2D flakes with the general formula $M_n\text{TX}_n\text{T}_x$ ($n = 1, 2, 3$) were left behind when such an A-layer of a MAX phase was removed. T denotes a boundary termination, most frequently fluorine (F), hydroxyl (OH), or oxygen (O) atoms. The first MXene was found in this manner. MXenes are a class of 2D crystalline materials with thin atomic layers and possibly infinite lateral dimensions. Because of their surface atom termination, they differ from each other in regards their features.

Due to their many useful intrinsic characteristics, MXenes have received significant attention. Exceptional metallic permeability, arising from an excess of electrons at the Fermi level, is one of these characteristics (EF); hydrophilicity because of an abundance of water-loving large interfacial terminations; and simplicity in processing solutions without the use of dispersants. Because they possess these special qualities, they are advantageous for a variety of potential applications, including EMI shielding, terahertz insulating, electrochemical energy battery storage, optoelectronics, flexible and transparent electrodes, detectors, thermal heaters, light-emitting diodes (LEDs), and anti-bacterial films [2, 4].

The typical structure for the MXene family is $M_{n+1}\text{X}_n$, whereby M stands for metallic elements (such as Sc, Ti, Zr, Hf, V, Nb, Ta, Cr, Mo, etc.) and X is either carbon or nitrogen. The MXene family is made up of transition metal carbides,

carbonitrides, and nitrides. The term “MXene” was chosen to identify the primary ternary carbide and nitrides, or MAX phases, from which MXenes are produced as well as to emphasize the parallels between this 2D material family and graphene. The typical formula for the 5 MAX phases is $Mn + 1AX_n$, where A denotes elements representing groups 13 and 14 of the periodic table. These phases are stacked ternary carbides and nitrides.

By etching Al-based Ti_3AlC_2 MAX in a strong hydrofluoric (HF) acid, Naguib et al. [4] reported the first MXene ($Ti_3C_2T_x$) in 2011. By adding imitators with strong hydrophilicity and dispersion stability in aqueous dispersions, the surface of the MXene layers was concluded with functional groups such $-O$, $-OH$, and $-F$ in the wet etching environment, which eliminated the aluminum layers. $Ti_3C_2T_x$ MXene, a member of the MXene family and a representative, stands out from other 2D materials thanks to its exceptional electrical, electrochemical, optoelectronic, and mechanical characteristics. This has led to the investigation of other MXenes with various elemental compositions, including M_5X_4 , M_4X_3 , M_3X_2 , and M_2X . The list of traditional single M and X layer MXenes was then further broadened by binary transition metal compositions (M1 and M2) and solid solutions (X1 and X2), which provided a wide variety of tuneable electrical and optical characteristics. Partially delaminating and forming lamellas with thicknesses ranging from tens to hundreds of nanometers are possible as a result of mechanical deformation of the MAX phases, which is mediated by basal dislocations and is very anisotropic. But none of the MAX phases have ever exfoliated into graphene-like crystalline layers just a few nanometers thick. Additionally, as far as we are aware, there are no reports on the selective removal of the A-group layers from the MAX phases and/or their exfoliation in the liquid or gas phases at room temperature or at mild temperature. In this article, we present the results of the Al extraction from Ti_3AlC_2 and the creation of a novel 2D material that we suggest to designate as “MXene” to highlight its graphene-like shape [4].

A novel kind of 2D material, MXenes possesses multiple pros that can be considered in various applications, including tremendous conductivity, tunable surface chemistry, hydrophilicity, high mechanical strength, versatile synthesis routes, layered structure for ion intercalation, high adaptability, and a large number of functional groups. Despite being promising materials, MXenes have few cons. The use of very hazardous hydrofluoric acid (HF) during their manufacture is a significant obstacle. Furthermore, MXenes have a propensity to self-stack and have low oxidative stability, which restricts their usefulness. Lastly, their broad implementation is hampered by the ongoing development of cost-effective synthesis techniques and industrial production methods [4].

MXenes can enhance the performance of these materials by improving conductivity, mechanical properties, and electrochemical efficiency. For example, MXene-based composites are used in supercapacitors and batteries for better charge storage, in sensors for heightened sensitivity, and in water filtration for efficient removal of contaminants. However, challenges such as scalability, stability, and cost still need to be addressed. Despite these hurdles, ongoing research suggests that MXenes and their

composites will play a pivotal role in advancing next-generation technologies in electronics, energy storage, and environmental applications.

Energy storage and supercapacitors: MXenes are widely used in supercapacitors due to their high conductivity, large surface area, and ability to intercalate ions efficiently. Their composites with carbon materials (like graphene or CNTs) have shown improved charge/discharge rates and energy densities. **Lithium-ion and sodium-ion batteries:** MXene composites are being explored as anodes and cathodes for next-generation batteries, where they improve the cycle stability, capacity, and overall efficiency. **Electromagnetic shielding** due to their high conductivity and ability to interact with electromagnetic waves, MXenes and their composites are utilized for electromagnetic interference (EMI) shielding materials. This is crucial in protecting electronic devices from external electromagnetic radiation. **Water purification and filtration:** MXenes have shown promise in water treatment applications, particularly for removing heavy metals, organic pollutants, and even salts. Their high surface area and tunable chemistry enable them to capture and filter out a wide range of contaminants. **Sensors and detection:** MXenes and their composites are being used in chemical, gas, and biosensors. Their large surface area, conductivity, and tunable surface chemistry allow for sensitive detection of various analytes, from hazardous gases to biomolecules. **Catalysis:** MXenes' high surface area and conductive nature make them suitable candidates for catalytic reactions, including hydrogen evolution reactions (HER), oxygen reduction reactions (ORR), and other electrochemical processes. **Flexible electronics:** MXenes are being integrated into flexible, wearable electronic devices. Their high conductivity and mechanical flexibility allow for the development of stretchable conductors, sensors, and energy storage devices.

2 | Synthesis Methodologies of MXenes

There are numerous methods for making MXene materials that have been documented in the literature, and one synthesis method can be advantageous versus another. To establish the ideal material for the task, one must be familiar of the ultimate result, the necessary qualities, and the materials warranted while synthesizing any kind of MXene. Alhaben et al. had detailed the various etching and delamination methods and the further processing required for the sample extraction in optimal conditions in Figure 2 [3].

Here, we go through some of the procedures used and provide detailed instructions for producing titanium carbide ($Ti_3C_2T_x$) and molybdenum carbide at room temperature as shown in Figure 2. The most researched and utilized MXene is Mo_2TiC_2 . In this review, we cover methods for storing, preparing, and depositing various conductive $Ti_3C_2T_x$ and (Mo_2TiC_2) MXene films [5].

The first step in making MXene is to etch the A-element atomic levels (for instance, aluminum) from the $Mn + 1X_n$ layers next to the A-element layers using a MAX phase (for instance, Ti_3AlC_2). The resulting MXenes following the etchant treatment executed by Alhaben et al. are represented in Figure 3 [3].

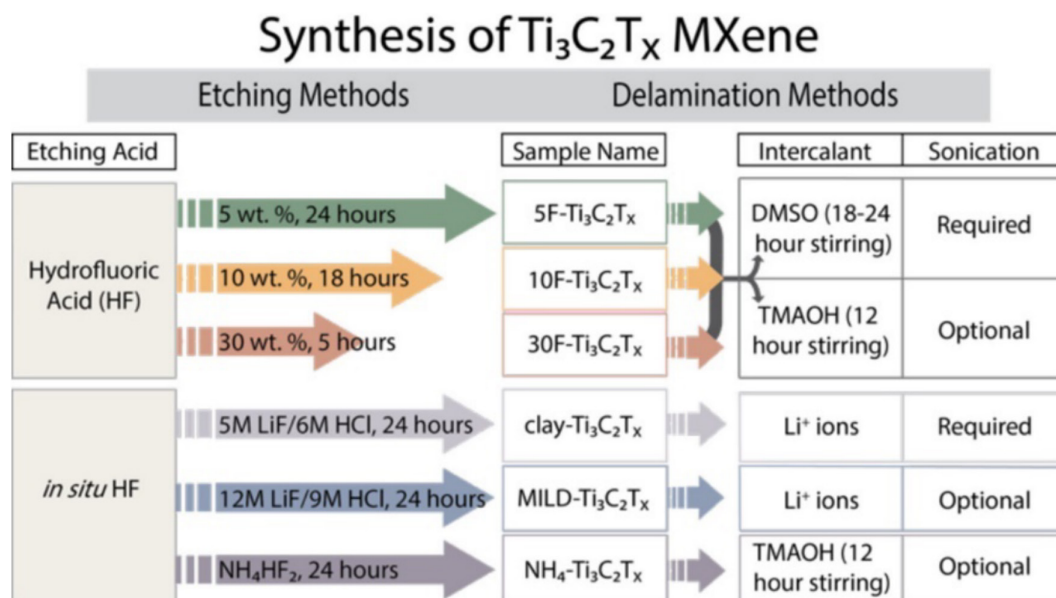


FIGURE 2 | Various synthetic strategies for $\text{Ti}_3\text{C}_2\text{T}_x$ MXenes [3].

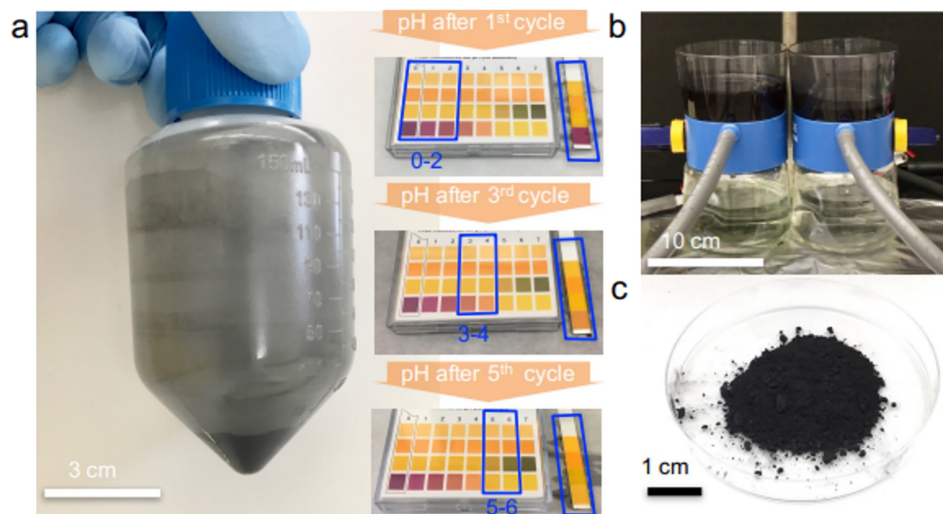


FIGURE 3 | $\text{Ti}_3\text{C}_2\text{T}_x$ powder that has been laminated and sedimented was prepared using HF or NH_4HF_2 and clean supernatant. (a) Following centrifugation procedures, $\text{Ti}_3\text{C}_2\text{T}_x$ was recovered using vacuum assisted filtering. (c) An optical picture of 5F- $\text{Ti}_3\text{C}_2\text{T}_x$ powder after 80°C vacuum drying [3].

The multilayered MXene sheets that are synthesized by the etching techniques (for instance, $\text{Ti}_3\text{C}_2\text{T}_x$) have hydrogen bonds holding the 2D layers together. After the etching is accomplished (i.e., the A-element layers have been completely removed), washing is necessary to get rid of any remaining acid and reaction by-products (salts), as well as to reach a safe pH [6]. Repetitive centrifugation is often used during washing to remove the MXenes from the acidic solution, followed by the decantation of the acidic supernatant. The product may be collected, for example, using vacuum-assisted filtering and dried in vacuum after the pH is raised to 6. The remainder of this research will concentrate on the creation and processing of $\text{Ti}_3\text{C}_2\text{T}_x$, one kind of MXene [6, 7]. The various strategies adapted by researchers to create different structures of MXenes are shown in Figure 4 [8].

MXenes are a diverse class of 2D materials derived from layered MAX phases by selectively etching out the “A” element, typically using chemical or electrochemical methods. The most well-studied MXene is $\text{Ti}_3\text{C}_2\text{T}_x$, synthesized from Ti_3AlC_2 using HF or a safer *in situ* method involving lithium fluoride (LiF) and hydrochloric acid (HCl), which generates HF in the reaction mixture. Ti_2C , derived from Ti_2AlC , follows a similar route but typically yields thinner flakes. Nb-based MXenes, such as Nb_2C from Nb_2AlC , are also synthesized using HF, though molten salt methods using ZnCl_2 or similar salts are often more effective for these types due to their resistance to HF etching. For Mo_2C , the precursor $\text{Mo}_2\text{Ga}_2\text{C}$ is not compatible with traditional HF etching; instead, molten salt etching is used to remove the Ga layer at high temperatures. V_2C , synthesized from V_2AlC , can be obtained using either HF or

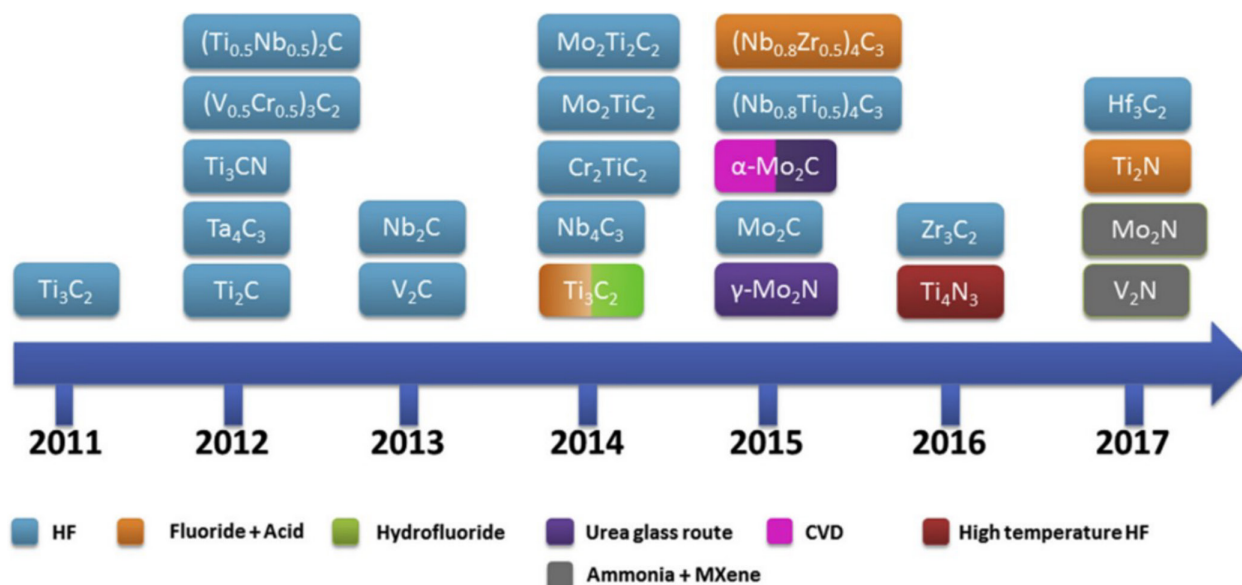


FIGURE 4 | An overview of the etching techniques employed to create MXenes from their development in 2011 to 2017 [8].

fluorine-free methods, which are increasingly preferred in biomedical and environmental applications. Cr₂C and Ta₄C₃, synthesized from Cr₂GaC and Ta₄AlC₃, respectively, are more niche MXenes typically requiring molten salt etching due to the stability of their A-layers. After synthesis, these MXenes often undergo delamination through intercalation agents like DMSO or TBAOH followed by sonication to produce monolayer or few-layer flakes. The choice of synthesis method directly influences the surface chemistry (e.g., -F, -OH, -O terminations), layer spacing, conductivity, and applicability in fields like energy storage, sensing, and catalysis.

Beyond the traditional synthesis methods like HF etching, in situ HF generation, and molten salt techniques, researchers have developed several alternative approaches to synthesize MXenes in a safer, more environmentally friendly, and tunable manner. Fluoride-free acid etching employs strong acids such as hydrochloric or sulfuric acid, sometimes with oxidizing agents like hydrogen peroxide, to selectively remove the A layer without introducing fluorine. This method is advantageous for applications where fluoride contamination must be avoided, though it typically yields lower-quality MXenes or works only with specific MAX phases. Similarly, alkali treatments using sodium or potassium hydroxide under heat or hydrothermal conditions offer a fluoride-free path, particularly for nitride-based MXenes, although they risk damaging the MX structure if not carefully controlled. Hydrothermal and solvothermal techniques also provide scalable, high-yield synthesis routes under controlled high-pressure, high-temperature environments, allowing for tailored surface terminations and improved environmental compatibility. Ammonium bifluoride (NH₄HF₂) etching has emerged as a milder and safer alternative to concentrated HF, offering ease of handling and safer waste management while still effectively removing A layers. Plasma etching, though more often used for surface modification, can also serve as a nonwet etching method under specific conditions, allowing for precise control over surface terminations. In addition, sonochemical methods use ultrasonic waves to enhance etching and exfoliation

processes, increasing efficiency and reducing processing time. More experimental approaches, such as salt-templated synthesis and self-assembled precursors, aim to create MXene-like structures with predesigned layer compositions that facilitate easy A-layer removal. These alternative methods are crucial in broadening the scope of accessible MXenes, reducing toxicity and environmental impact, and enabling tailored synthesis for specialized applications.

2.1 | Hydrogel and Foam Synthesis

Ti₃C₂T_x is the sol-gel used to create all-MXene hydrogels, which are then filtered with vacuum. They were able to produce a Ti₃C₂T_x hydrogel despite the fact that this technique is often used to create MXene “paper” sheets by simultaneously cutting off the vacuum as quickly as no coagulant was left on the porous membrane. The hydrogel layer was thereafter briefly submerged in acetone to aid in its separation from the slurry. After being removed by moderators, which was before water molecules’ significant presence, caused a dynamical physical crosslinking among the MXene sheets, which gives the material its characteristic gel-like structure. Figure 5 represents how the pre-intercalated hydrogen atoms in the MXene architecture allow for rapid proton transfer [2, 9, 10].

Ion diffusion-induced gelation was used to create MXene-based hydrogels. To create homogenous mixes, the different volume ratios of MXene and GO concentrations were lowered to 3 mg mL⁻¹, respectively. With diluted HCl, the mixture's pH was raised to 1.7–3.0. The acidified solution was then covered with a portion of metal foil (Zn, Al Co, Ni, and Fe) for the predetermined amount of time. Following the gelation procedure, a portion of hydrogel that had developed on the metal foil was taken and placed in HCl solution in order to separate the hydrogel from the metal substrate. An MXene-based hydrogel that is freestanding and hydrated is created by dialysis in deionized water for 2 days. Subsequently, the hydrogel as-made was immediately freeze-dried to produce the MXene foam [11].

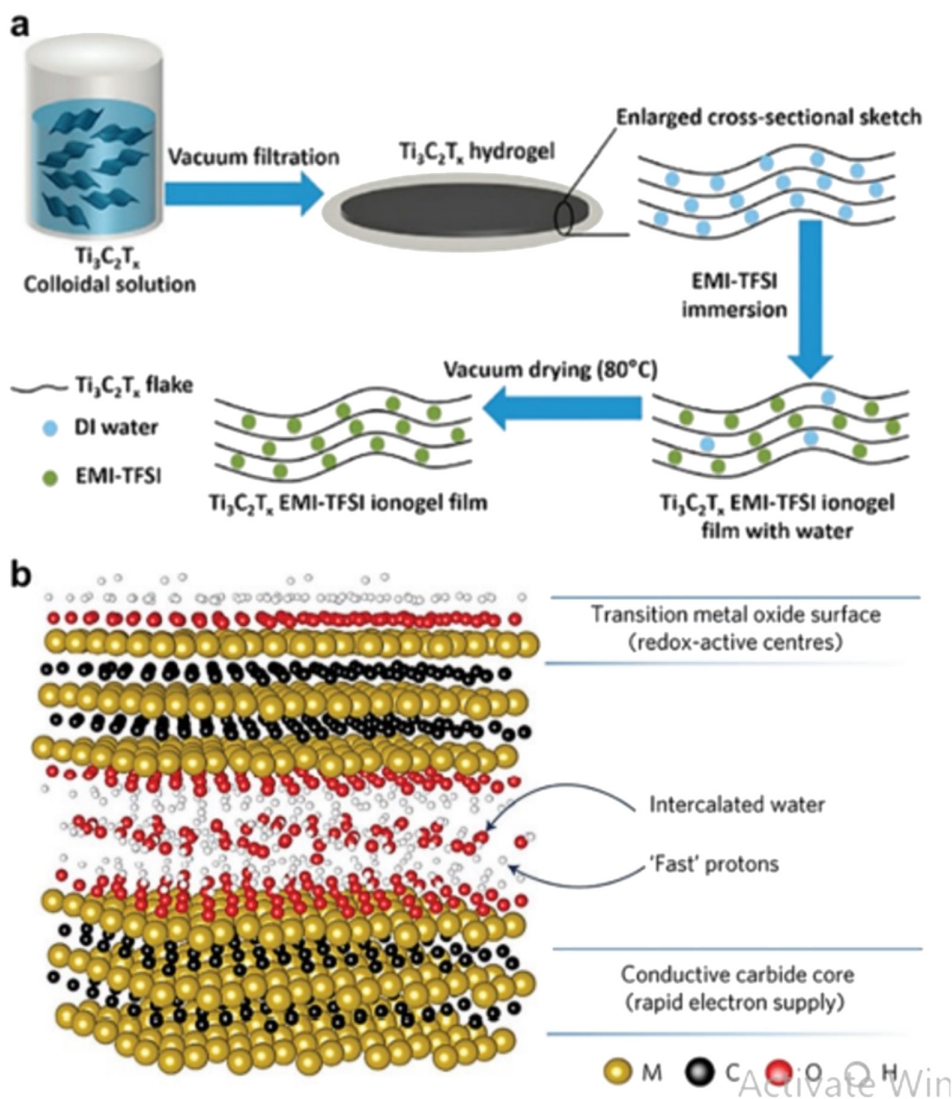


FIGURE 5 | (a) Representation of the development of an all-MXene hydrogel and ionogel in a schematic (b) representation of how the pre-intercalated hydrogen atoms in the MXene architecture allow for rapid proton transfer [2].

2.2 | Chemical Vapor Deposition

Methane was used as the substrate for C in the development of the chemical vapor deposition (CVD) method, with a copper (Cu) foil placed over a molybdenum (Mo) foil serving as the substrate. Experiments were carried at a temperature greater than 1085°C . The breakdown of substances on the substrate's base layer during CVD results in the formation of material layers from the vapor phase. As a result of the Cu foil melting due to the high temperature, a Mo-Cu alloy was created at the liquid Cu/Mo contact. This caused Mo atoms to diffuse to the liquid Cu's surface where they reacted with the C atoms released during the breakdown of methane to create Mo_2C crystals. The compound that has been created, despite it resembled MXene in structure, was really a 2D transition metal carbide with a higher surface area than the nanosheets that have been created. Researchers were able to create 2D ultrathin— Mo_2C crystals with transverse diameters more than 100 nm but a few nanometers in thickness. The amount of methane utilized, and its flow concentration allowed them to regulate the thickness. The resulting MXene-like substance

was flawless, and after many months of exposure to air, its superconductivity remained constant [12–14].

2.3 | Hydrothermal Method

The hydrothermal method is a technique that uses sodium hydroxide to extract $\text{Ti}_3\text{C}_2\text{T}_x$ MXene from the Ti_3AlC_2 MAX phase (NaOH). This process involves attacking the aluminum (Al) layers with hydroxide anions (OH), which causes the Al atoms to oxidize. Alkali is subsequently used to decompose the generated Al hydroxides, and the exposed Ti atoms are then eliminated by OH or O. New Al hydroxides that are contained in the lattice from the Ti layers and cannot further react with the OH may still be created as a result of the procedure. A succession of hydrothermal temperatures and concentrations of NaOH water treatments in an argon environment was used to solve the issue. This hydrothermal process produces MXenes that have more OH and O terminations than their HF-etching equivalents, which greatly improves their supercapacitor efficiency and is shown in Figure 6 [8].

2.4 | Electrochemical Method

For the debonding of Ti_3C_2 in a binary aqueous electrolyte, an electrochemical technique involving the use of F was first suggested. Bulk Ti_3AlC_2 was used as the anode and cathode in the construction of a two-electrode system. Just the anode went through the etching procedure, yielding $\text{Ti}_3\text{C}_2\text{T}_x$. They utilized a mixture of 1-M NH_4Cl and 0.2-M tetramethylammonium hydroxide (TMAOH) with a pH of 9. This prevented the etching from just occurring on the anode's surfaces and allowed the electrolyte ions to infiltrate into the anode's deeper layers. The bulk anode progressively delaminated when a low voltage of 5 V was applied. To create individual sheets of $\text{Ti}_3\text{C}_2\text{T}_x$, the sediment and suspended powders of $\text{Ti}_3\text{C}_2\text{T}_x$ were then crushed and added to 25% w/w TMAOH [15, 16].

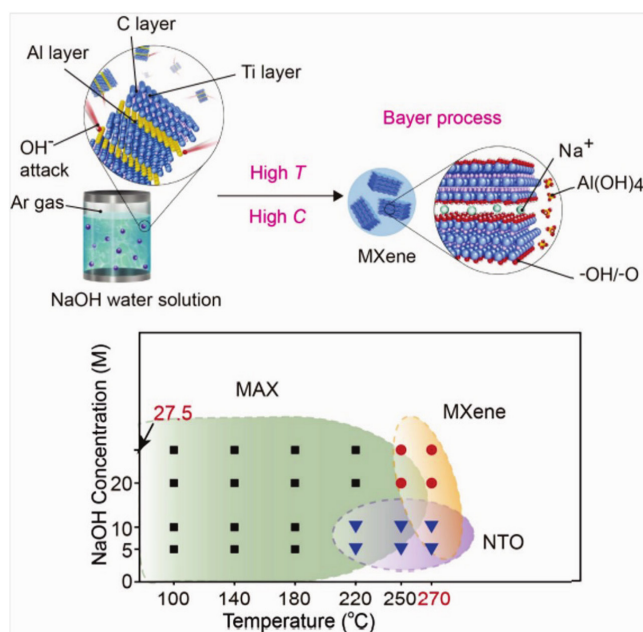


FIGURE 6 | Synthesis of MXene by hydrothermal technique method [8].

The resulting MXenes had electrochemical performance that was comparable to that of those made using HF or HCl/LiF. But considering the total etching yield, the electrochemical approach seems to be the most promising, since up to 60% of the solid matrix may be converted into $\text{Ti}_3\text{C}_2\text{T}_x$.

2.5 | Molten Salt Etching

In 2016, MXenes were etched using molten salt for the very first time [17]. Fluoride salts and $\text{Ti}_3\text{C}_2\text{T}_x$ nanoparticles were mixed in a 1:1 mass ratio, and the solution was then heated at 550°C for 30 min. Al was found to be present in five different fluoride stages, but the absence of fluorides including Ti corroborated the selective character of both the etching. They used diluted sulfuric acid (H_2SO_4) to dissolve the fluorides that contained aluminum, and then they removed the etching effects by washing with deionized water, centrifuging, and dewatering. Based on the XRD pattern, which showed that almost all of the fluoride salts had been removed, the resulting powder was $\text{Ti}_4\text{N}_3\text{T}_x$, wherein T refers for either OH or F surface terminations. However, $\text{Ti}_4\text{N}_3\text{T}_x$ was not etched. Tetrabutylammonium hydroxide (TBAOH) was added to the powder, after which it was separated by centrifuging and decanting after being washed with deionized water. The multilayer $\text{Ti}_4\text{N}_3\text{T}_x$ -MXenes was further broken down during this procedure. Following centrifugation, probe sonication, and dilution with deionized water, the remaining powder was processed. The relatively small unlayered $\text{Ti}_4\text{N}_3\text{T}_x$ flakes were obtained after the product was filtered. The MXenes produced had higher atomic flaws than the one synthesized using HF-etching, which decreased the material's fracture resistance and represented in a schematic in Figure 7.

2.6 | Fabrication of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene and Graphene Oxide Composites

To produce a well-constructed hydrogel system, more susceptible crosslinking sites must be exposed. Another 2D resource

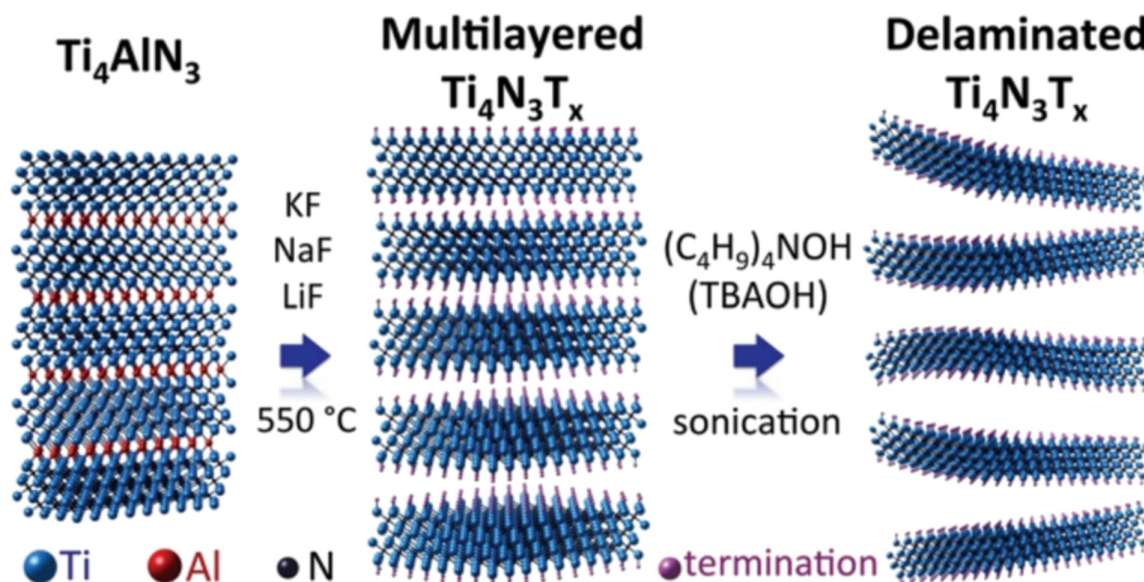


FIGURE 7 | Schematic representation of synthesis of $\text{Ti}_4\text{N}_3\text{T}_x$ by molten salt etching technique [17].

gelator, GO, might help with this by enabling interfacial exchanges as opposed to merely point-to-plane connections with both the MXene nanomaterials.

A gentle etching technique was employed to produce $\text{Ti}_3\text{C}_2\text{T}_x$ MXene of the highest grade. Typically, 20 mL of 9-M HCl were used to dissolve 1 g of LiF (Alladin) while stirring in an ice-water bath. After that, 1 g of Ti_3AlC_2 powder that had been sieved (400 mesh) was gently added while the reaction temperature was maintained at 35°C. After a 24-h reaction, the product was periodically rinsed with deionized water before being gently sonicated beneath an Ar flow to separately identify it and produce $\text{Ti}_3\text{C}_2\text{T}_x$ MXene suspension. GO was synthesized using a modified Hummers process and then purified thereafter. The GO was repeatedly washed in excess HCl (15 wt%) in order to successfully eliminate the by-products. After then, the GO was cleaned with acetone and water to get rid of any remaining HCl and contaminants as shown in Figure 8 [11]. The GO was then re-dispersed in water and ultrasonically exfoliated before being used again [7, 18, 19].

The impressive ability of $\text{Ti}_3\text{C}_2\text{T}_x$ to function as a reducing agent is thought to be due to the multivalent disposition of its Ti species, which can change from a low-valence to a surface-terminated high-valence state gelation process. The reduced electrostatic repulsion between $\text{Ti}_3\text{C}_2\text{T}_x$ and rGO also makes it easier for the MXene nanosheets to self-converge into the anisotropically constructed rGO framework, which is fuelled by the hydroxyl group as shown in Figure 9. By exploiting the redox capacity of $\text{Ti}_3\text{C}_2\text{T}_x$ in reducing Pd ions to metals Pd, which has been progressively inscribed on the MXene sheets, equivalent exciton oxygenation at the interface was also employed to create Pd-decorated $\text{Ti}_3\text{C}_2\text{T}_x$ hydrogel [20, 21].

2.7 | Various Types of Synthesis Methods

The main synthesis routes for MXenes are well-established (etching-based methods), a few lesser-known, emerging, or hybrid techniques are also being explored. These are generally more experimental or niche, but they aim to address limitations

like toxicity, scalability, and control over surface chemistry. Here are additional or alternative synthesis techniques beyond the conventional ones:

- **Topochemical conversion-concept:** Transform layered precursors (not necessarily MAX phases) into MXenes via chemical reactions without breaking down the lattice structure; example: conversion of $\text{Mo}_2\text{Ga}_2\text{C}$ into Mo_2C by selective removal of Ga and rearrangement of the layers. Benefit: Enables synthesis of non-MAX-based MXenes (e.g., Mo, W, V-based) that are difficult to make using traditional routes.
- **Solid-state reactions and diffusion-controlled synthesis-method:** Use a diffusion process at high temperature where M, A, and X atoms are slowly diffused in specific ratios, often layered, to form MXenes in situ; goal: avoid the use of chemical etchants altogether and grow MXene-like structures directly; use case: still in early-stage research, especially for doping or heterostructure formation.
- **Laser-assisted or plasma-assisted etching, laser ablation:** Laser energy is used to selectively remove the A-layer; plasma etching: fluorine or chlorine plasma can be used for cleaner, more controlled A-layer removal.; pros: highly localized, patternable, and can be integrated with microfabrication and cons are required specialized equipment; not scalable yet.
- **Reductive etching/chemical reduction-idea:** Use reducing agents (e.g., NaBH_4 , hydrazine) to remove A-layer or modify surface terminations; goal: introduce more —OH or —O functional groups and avoid fluorine completely; applications: tunable surface properties, useful for biocompatibility and catalysis.
- **Magnetically-assisted synthesis, experimental concept:** Use of magnetic nanoparticles or fields to align or separate layers during or after etching; application: better control over delamination or structure formation in MXene composites.
- **Self-propagating high-temperature synthesis (SHS)-method:** Exothermic reaction propagates rapidly through

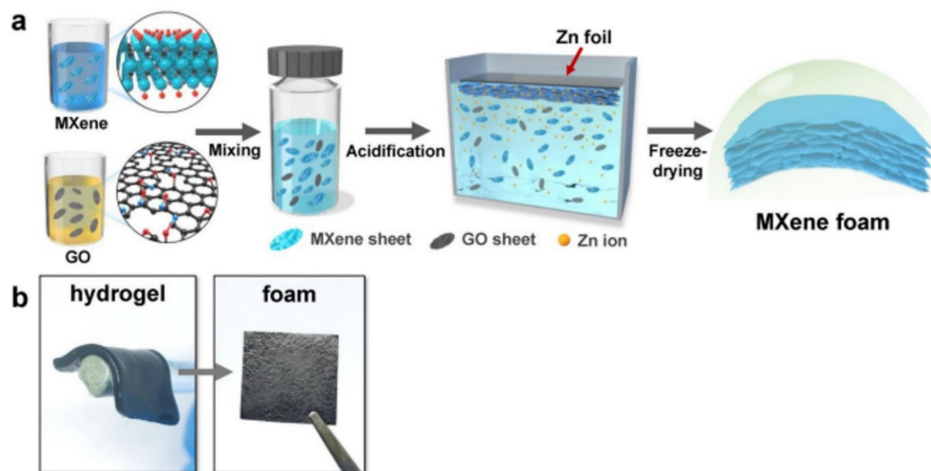


FIGURE 8 | Synthesis of GO-MXene hydrogel and foam [11].

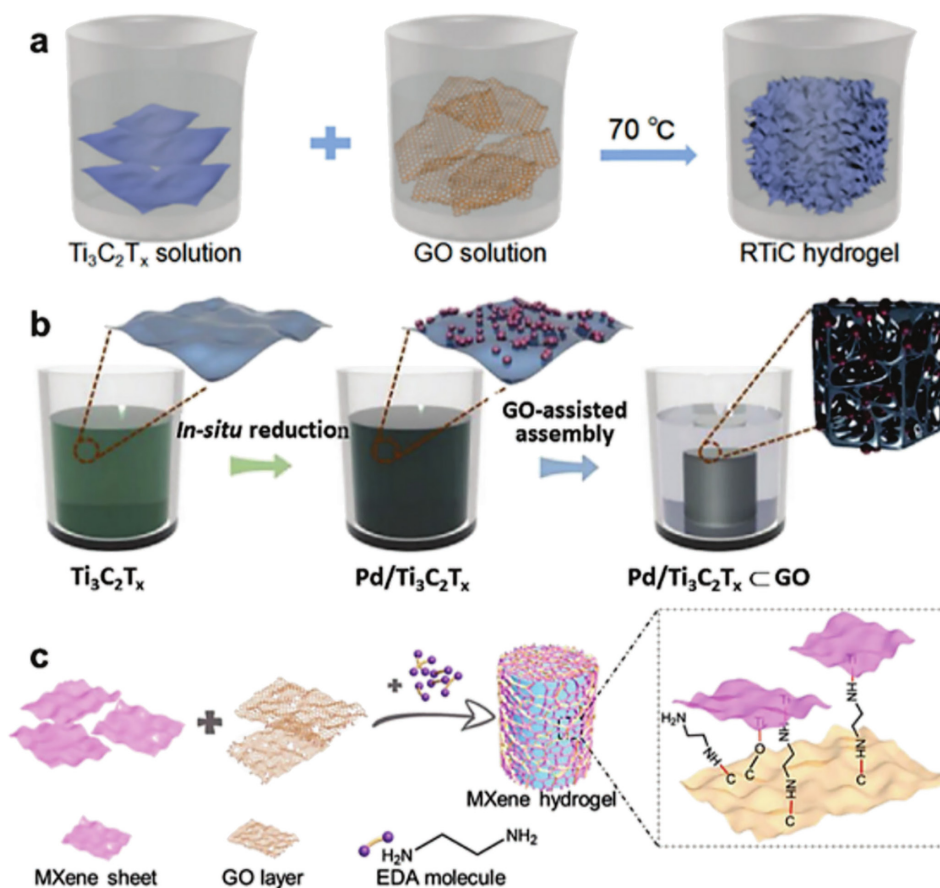


FIGURE 9 | Schematic depiction of the gelation of several MXene hydrogels with GO assistance. $\text{Ti}_3\text{C}_2\text{T}_x$ -rGO hydrogel (b) $\text{Ti}_3\text{C}_2\text{T}_x$ -rGO hydrogel with Pd decorations (c) A $\text{Ti}_3\text{C}_2\text{T}_x$ -rGO hydrogel developed by EDA [2].

the precursor materials to form MAX or MXene phases; use case: typically used to synthesize MAX first, but modifications aim to go directly to MXene or aid its formation. Advantages are energy-efficient, potentially scalable.

- Green and bio-assisted synthesis (early stage)—Using plant extracts, enzymes, or mild biomolecules to assist in etching or exfoliating MXenes; goal: environmentally friendly synthesis, possibly for biomedical or biosensor applications; example: use of citric acid or amino acids to help exfoliate MXene layers.

These methods are not yet widely adopted, but they are being explored to overcome the limitations of fluoride-based chemical synthesis, especially for: Fluorine-free MXenes, 2D materials beyond Ti-based MXenes, and functional surface control.

3 | Applications Based on Unique Properties of MXenes

3.1 | Electrochemical Properties and Sensor Applications

When compared with other 2D materials like graphene, MXenes stand out due to their electrical properties. Current findings have shown that the metal sheets (M-layer) are the main

component controlling the electrical properties of MXenes. In order to regulate the electrochemical characteristics of a 2D carbide beyond metallic to semiconductor-like, it is known that a delicate balance among temperature and oxidizing agent activity must always be maintained. It is also known that the two lateral transition M-layers of the material may be adjusted. Owing of surface termination and varying degrees of imperfections, the manufacturing techniques may also affect electroconductibility. Due to the loss of the ordered structure for free electron movement, MXenes have poor electroconductivity the more flaws there are. Charge imbalance defects will be created by the interchange of ions with various electric densities. MXenes often have $-\text{OH}$, $-\text{O}$, and $-\text{F}$ functional groups on their surface since fluoride makes up the majority of the etching solution. The electrical conductivity of MXenes has altered in accordance with the modification of the surface termination [15, 22].

The conductivity/resistivity of an MXenes-based sensor can be tuned by subjecting it to strain changes as the fracture size increases. MXenes are extensively used in biosensors to detect the rapid identification of various gases, ions, and biomarkers. When molecules cling to the surface terminal of MXenes with varying compositions and concentrations, the conductivity will fluctuate. By using MXenes materials of various compositions, different molecules may be selectively adsorbed, and this results in a clear shift in conductivity-based sensing studies [16, 23, 24].

3.2 | Biocompatibility and Tissue Engineering Applications

The construction of MXene nanostructures and their materials have unique variety of combination during creation. Transdisciplinary researchers in the field of biomedical and therapeutic applications have taken an interest in 2D MXene materials due to their exceptional physiochemical capabilities as well as distinctive planar structure [25]. They show promising potential for various applications, such as bioimaging, cell tomography, precision medicine, tissue engineering, regenerative medicine, and drug delivery. There are still significant difficult problems relating to their consistency in biochemical surroundings, continual drug release profile, and biological systems' interaction [26–28]. Szuplewska et al. explains that titanium carbide MXenes composite nanofibers can be created as exceptional biomaterial for tissue engineering and cell culture is titanium carbide. This new class of biomaterials has the potential to close the bridging gap between materials science and stem cell-based tissue therapies and future multifunctional biomedical therapeutics [29]. The clinical use of tissue-engineered cardiac patches made of MXenes for myocardial infarction shows promising potential. These patches have similar arrangement of the native extracellular matrix and the electroconductivity of the human cardiac tissue. In their research, a novel composite construction that may give human induced pluripotent stem cell-generated cardiomyocytes for cardiac tissue engineering applications both electrical and morphological characteristics was created [30]. MXene quantum dots (MQD) are great candidates for a variety of clinical and biomedical devices, including genetic sensing/imaging, cancer prognosis, regenerative medicine, tissue engineering, drug/gene delivery, and analytical biochemistry, due to their distinctive architectural, optical, magnetic, and electrical properties. Not only for MXene QD-based nano systems but also for additional smart tools and hybrid nanocomposites including MXenes with enormous clinical and biological potentials, rise and improved production procedures have been devised [31]. Iravani et al. explains that the MXene possesses several unique qualities, including a very high surface area to volume ratio, superior conductance, bioactivity, renewability, water dispersibility, antibacterial properties, and more. Concentrated on the development and deployment of MXene and MXene-based composites in the tissue engineering of the skin, bone, nerve, and heart, interdisciplinary researchers in the field of biomedical and therapeutic applications have taken an interest in 2D materials due to their exceptional physiochemical capabilities as well as distinctive planar structure [32]. The various salient points of MXenes used in tissue engineering and regenerative medicine are described in Figure 10.

3.3 | Luminescence Properties and Nanomedicine

Huang et al. provide source information to overcome the inherent constraints of traditional materials; the rise of 2D composites has generated considerable interest in their potential uses for nanomedicine and biomaterials. They are composed of transition metal carbides/nitrides and have generated significant interest in biological applications. The second near-infrared bio window with extensive tissue entry can be used for photonic hyperthermia treatment due to their photothermal energy-conversion capacity [32]. With a unique planar nanostructure, physiochemical

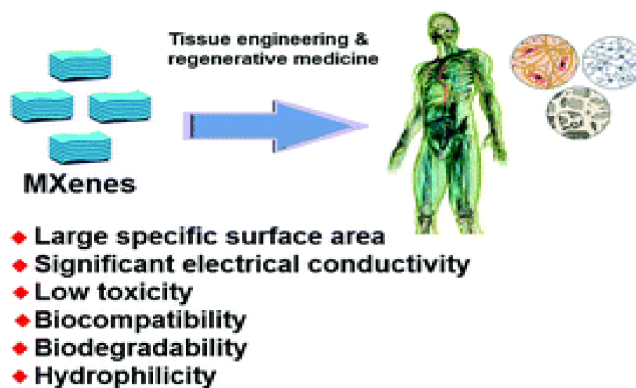


FIGURE 10 | MXenes applications in tissue engineering field and their significant parameters [32].

characteristics, and biological effects, transition metal carbide, carbonitride, and nitride have generated booming research interest in a variety of applications spanning from energy transformation to biomedicines, highlighting the intrinsic chemistry of these molecules as theranostic nanomedicine agents, with particular attention to the synthesis of MXenes, surface engineering, physiochemical properties, and biosafety assessment [33]. Smart zero-dimensional titanium carbide MQD with unique surface modifications were created to study the subcellular nanomedicine possibilities. Within 24h of cell culture, MQD absorption into human ECs was demonstrated to occur spontaneously. During this, there were no discernible morphological changes in the cells, and MQD localization was found to be extremely stable. This groundbreaking discovery signals encouraging advancements in the use of MQD in nanomedicine [34]. In their research, Zhong et al. clearly denote that MXene-based nanomaterials can be utilized directly as nanodrugs, as platforms for drug delivery in photothermal therapy, or as therapies for the treatment of cancer. We also go through how these materials might be used for magnetic resonance and photoacoustic imaging methods in biosensing and bioimaging. The most noteworthy applications of MXenes are that they act as effective antibacterial and environmental therapies, along with a brief talk of their possibilities and difficulties in the future. Quantum dots in the blood will come into direct touch with vascular endothelial cells when they are used as fluorescent probes or drug detectors for in vivo imaging. It is important to research whether quantum dots, which are injected into blood arteries as imaging agents, can impact endothelial function. The toxic effects of quantum dots have been the subject of various investigations in recent years. The toxicity of five different types of quantum dots, such as those for cell imaging, Cd-containing quantum dots, CuInS₂ quantum dots, black phosphorus quantum dots, MQD, and carbon-based quantum dots, can be known. Even though the results of recent studies on toxicity are inconsistent, they can never predict the analysis for material cytotoxicity [35].

MXenes, a novel class of 2D transition metal carbides, nitrides, and carbonitrides, have attracted increasing attention in nanomedicine due to their unique physicochemical properties, including high surface area, tunable surface chemistry, excellent electrical conductivity, and emerging luminescence behaviors. Although MXenes are traditionally recognized for their use in energy storage and electromagnetic shielding, recent studies

have begun to uncover and engineer their luminescent properties, making them promising candidates for bioimaging and phototherapeutic applications.

Native MXenes, such as $\text{Ti}_3\text{C}_2\text{T}_x$, are not inherently highly luminescent, but their luminescent behavior can be engineered through surface modifications, heteroatom doping, or quantum confinement effects when downsized to quantum dots (MXene QDs). These MQDs exhibit photoluminescence (PL) that can be tuned across a wide spectral range depending on their size, surface groups, and synthesis methods. For example, nitrogen-doped Ti_3C_2 QDs have shown strong blue to green emission, making them useful as fluorescent probes. The luminescence in MXene QDs arises mainly from surface defect states, edge states, and functional group interactions, and it is often excitation-wavelength dependent.

3.3.1 | Applications in Nanomedicine

In nanomedicine, luminescent MXenes and their QDs offer multifunctionality for both diagnostic and therapeutic purposes:

3.3.2 | Fluorescent Bioimaging

MXene QDs can act as nontoxic, photostable fluorescent markers for cell imaging, with some exhibiting efficient intracellular uptake and strong luminescence in the visible region. Their tunable PL makes them viable for multiplex imaging or tracking biological events in real time.

3.3.3 | Photothermal and Photodynamic Therapy (PTT/PDT)

Some MXenes exhibit excellent photothermal conversion under NIR light, and their luminescent forms can also generate reactive oxygen species (ROS) under light irradiation, enabling synergistic theranostic platforms (imaging + therapy). Combining luminescence with PTT/PDT enhances therapeutic precision by allowing imaging-guided treatment.

3.3.4 | Drug Delivery Monitoring

Luminescent MXenes can be engineered as stimuli-responsive drug carriers, where changes in luminescence indicate drug release, pH variation, or redox environment, supporting real-time monitoring of therapeutic action.

3.3.5 | Biosensing

The PL of MXenes is highly sensitive to surface interactions, enabling their use in fluorescence-based biosensors for detecting ions, biomolecules, or environmental changes.

MXenes are not intrinsically highly luminescent; advances in nanostructuring and surface engineering have unlocked their potential in luminescence-based nanomedicine. Their

multifunctional properties—combining imaging, therapy, and sensing—position MXenes as next-generation materials for precision medicine and noninvasive diagnostics.

3.4 | Photothermal Therapy

The MXene system displays excellent photothermal stability, biodefense, and histocompatibility throughout in vivo and vitro experiments due to surfaces to the MXene by Au nanoparticles. The various potential applications of MXenes in nanomedicine are shown in Figure 11. The system demonstrates synergistic photothermal ablation and chemotherapy for tumor treatment due to the strong photothermal transformation capability of both Au particles and MXenes.

These substances have excellent diagnostic and curative potential and present chances for photoacoustic imaging of cancer in addition to photodynamic and photothermal therapy. With the ability to transfer from vascular endothelial cells and particular identification, better consistency, and auto-fluorescence benefits at various emission-excitation wavelengths, MXene-based systems synthesized with suited biocompatible or bioactive agents have the necessary cellular uptake characteristics; this enables post-transport investigation and monitoring. MXenes surface engineering can enhance their photonic, physical, and electrochemical properties as well as their bio-compatibility, selectivity, bioavailability, and biodegradability, enabling the creation of multimodal systems with cancer theragnostic applications. The possibility of MXenes and their derivatives as cancer nanotheranostics with current developments and promising opportunities can be explored [35, 36]. The therapeutic target of iron metabolism is so appealing. Unfortunately, existing iron-based therapy approaches frequently show poor results and can cause toxicities that are not intended. The presentation of a dual-therapeutic prodrug that enables iron chelation chemo-photothermal activity in cancer therapy shows the iron chelation and chemotherapeutic properties that can be photo-activated at the tumor sites while potentiating a powerful photothermal effect with photothermal conversion efficiency improvements of up to 40%. The findings point to a potentially effective iron chelation-based phototherapeutic strategy for cancer treatment [37]. Song et al. suggest that a unique combination such as titanium carbide with MXene/gold nanorod nanosheets, a unique sandwich-like nanohybrid, has drawn a great deal of interest in the biomedical area because of their synergistically improved near-infrared responsiveness and significant absorption in the NIR range. Cancer therapy applications of MXenes are shown in Figure 12. Due to the increased NIR-responsiveness, the resulting nanocomposites displayed notable photothermal conversion efficiency. Additionally, the nanocomposites have pH- and NIR-responsive drug release behavior [30, 32, 38].

4 | MXenes for Food Industry Applications

Sensors based on MXenes have been extensively utilized to detect pesticide remnants, heavy metal ions, pathogenic microbes, and pathogens in food protection and quality monitoring. In the field of mycotoxins analysis, comparing with the previously reported sensors, the aptasensor achieved comparable linearity and higher sensitivity [39]. Deoxynivalenol (DON) is a mycotoxin

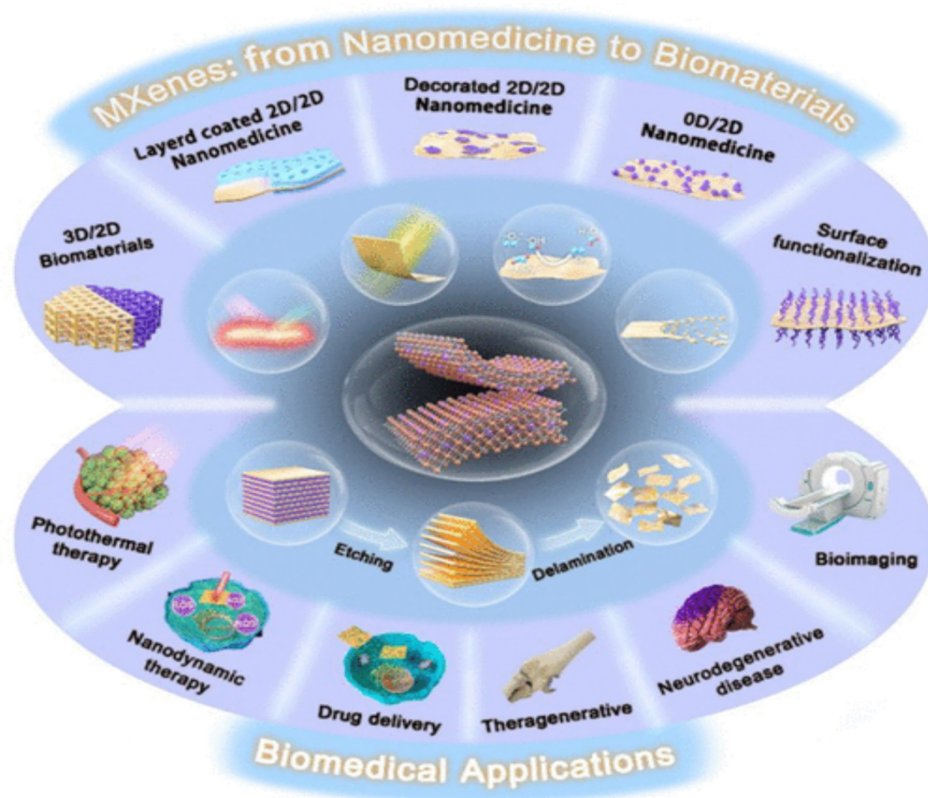


FIGURE 11 | MXenes application in the field of nanomedicine [35].

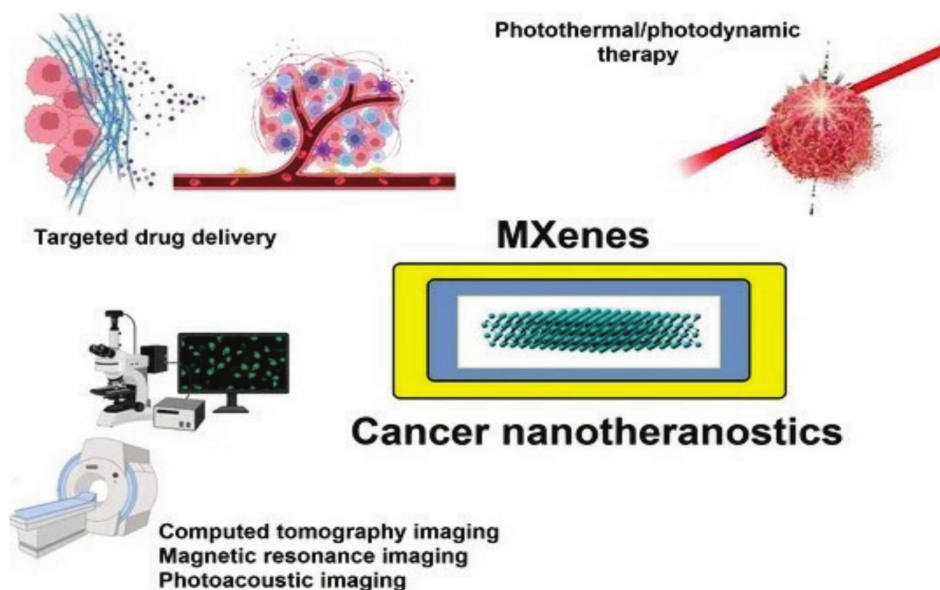


FIGURE 12 | MXenes being used for the application of cancer therapy using nanophototherapy [32].

member of the *Fusarium* species that secretes, and consuming it has major health consequences. Here, the MXene is used to generate a highly sensitive and selective biosensing system. aluminum is selectively etched from titanium aluminum carbide (Ti_3AlC_2 -MAX) powder utilizing HCl and LiF to do this (HCl-LiF). Another strategy included combining 2D MXenes with binding proteins aptamers, which led to the creation of creative aptasensing methods for clinical diagnostics and mycotoxin detection [40]. Another newly developed fluorescence biosensor

for AFB1 mycotoxin detection is based on MXenes. The aptasensors, also made of PVDF-coated MXene nanofibers, are used in the detection of Ochratoxin A in grape juice [41]. The density of states of the Ti_2CO_2 MXene family is represented in Figure 13.

MXene/polymer nanocomposite sensors are widely used in food industry, acts as smart packaging systems which monitors and records deterioration in the packaged foods. Ti_3C_2 is one of the thinnest layers in MXene family used to exploit applications in

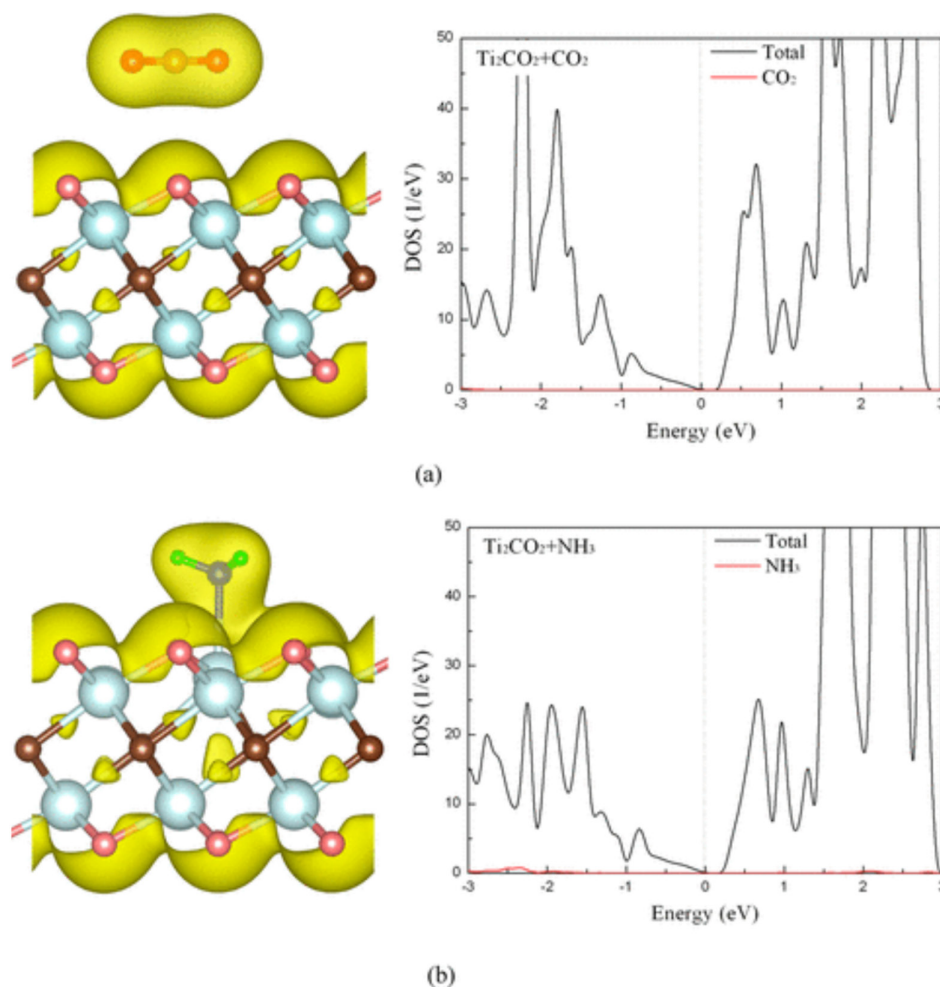


FIGURE 13 | MXenes in NH_3 sensing and capturing [41].

gas sensors sensing H_2 , NH_3 , CO , CO_2 , CH_4 in monitoring packaged meat spoilage [42]. In another study the food spoilage can be detected by monitoring the color change of glucose of food or beverages which is reported by Au/MXene nanocomposite for sensitive enzymatic glucose detection. The detection of H_2O_2 is important in the dairy industry, the shelf life of raw milk can be increased by adding a tiny amount of H_2O_2 after milking. Therefore, the study is addressed using MXene-based H_2O_2 sensors [41]. The sensors can be fabricated in such a way, bonding with the natural color pigments to act as food spoilage indication.

5 | MXenes in Environmental Monitoring and Remediation

Photocatalytic degradation is a technique for environmental clean-up that shows promise. Numerous photoactive semiconductors, including $\text{g-C}_3\text{N}_4$ and TiO_2 , have so far shown an improving propensity for the photocatalytic destruction (PD) of different organic polymers. For instance, Ti_3C_2 and TiSO_4 were used as precursors in the hydrothermal method by Gao et al. to create $\text{TiO}_2/\text{Ti}_3\text{C}_2$. The TiO_2 agglomeration was decreased by the Ti_3C_2 serving as a growth site for TiO_2 nanoparticles. The TiO_2 was distributed uniformly, which contributed to the excess of active sites for the photodegradation process.

Consequently, it has been shown that the directional development of TiO_2 on the surface of MXenes is an efficient way to increase the effectiveness of photocatalytic organic pollutants destruction [43, 44].

A photo-Fenton catalyst of Ti-based derived MXenes for dyes degradation. Further, Mashtalir et al. reported the first usage of MXenes for the degradation of MB and AB80 dyes under ultraviolet (UV) light. In the absence of light, the PD is achieved. In another report, Cao et al., studied antibiotic sulfamethazine degradation through photocatalytic activities of $\text{CuFe}_2\text{O}_4/\text{Ti}_3\text{C}_2$. $\text{CuFe}_2\text{O}_4/\text{Ti}_3\text{C}_2$ actions on the breakdown of the antibiotic sulfamethazine. Increased photocurrent density was shown in the produced $\text{CuFe}_2\text{O}_4/\text{Ti}_3\text{C}_2$ than in the pure CuFe_2O_4 and Ti_3C_2 , indicating extraordinary photo-generated charge carrier separation. This thorough analysis of the PD route employing nanomaterials based on MXene may open up new research avenues [45].

Besides, Chao et al. reported that the (111) surface influenced $\text{TiO}_2/\text{Ti}_3\text{C}_2$ ($\text{TiO}_2(111)/\text{Ti}_3\text{C}_2$) using the NH_4F -assisted hydrothermal oxidation reaction. The NH_4F contents added in the synthesis process were controlled to maximize the exposed ratio on the TiO_2 . According to the PD data, an increase in exposure resulted in an increased surface area that improved the MB dye degradation rate, that is, higher charge carrier efficiency. Jiao

et al. synthesized $\text{MoS}_2/\text{Ti}_3\text{C}_2$ nanocomposite using a hydrothermal method. According to the findings, pure Ti_3C_2 and MoS_2 did not display the $\text{MoS}_2/\text{Ti}_3\text{C}_2$ nanocomposites greatly improved photocatalytic activity [46]. The use of various MXenes and their outcomes in environmental applications is shown in Table 1.

6 | MXenes in Water Treatment Applications

6.1 | Dispersed Pollutant Adsorption

With their high conductivity, hydrophilicity, great structural stability, and adaptable surface chemistry, MXenes are developing transition metal nitrides, carbides, or carbonitrides, making them excellent prospects for water treatment and environmental remediation. For a variety of wastewater pollutants, MXenes in particular exhibit good sorption capability and effective reduction efficacy [26]. Numerous applications have benefited from the discovery of 2D nanomaterials. Application of MXenes in water/wastewater treatment can be categorized into many directions, namely, adsorbents, membranes, radionuclides, antimicrobial agents, and electrocatalytic sensors for electrochemical separation and deionization.

Adsorption, or adhesion technique of atoms to a surface, is a widely used water purification treatment due to its ease of operation, high removal efficiency, and comparatively cost efficiency. MXenes play a major role in water sorption, treating toxins (Figure 14). It is demonstrated that MXenes have a capability to adsorb several heavy metals such as copper (Cu), lead (Pb), mercury (Hg), and chromium (Cr). MXenes' surface groups also interact with the desired pollutant to adsorb them [54]. Peng et al. synthesized alk-MXene ($\text{Ti}_3\text{C}_2(\text{OH}/\text{ONa})_x\text{F}_{2-x}$). This, as anticipated by the density functional theory, is an ideal alternative for the adsorption of hazardous toxic substances, as shown in Figure 14 [55]. According to Wang et al., the $\text{Ti}_3\text{C}_2\text{T}_x$ material could also be a contender for creating reactive permeable barriers that might be used to remediate effluent from uranium mining. MXenes have also shown potential adsorption capabilities toward other heavy metal ions found in nuclear refuse, including Re (IV), Th (IV), and Eu (III) [56].

6.2 | MXenes-Based Membranes for Water Filtration

MXenes are suitable for water purification membranes due to their high surface area, flexibility, hydrophilicity, and high strength of 2D layers. 2D carbon nanomaterials, such as graphene and graphene oxide (GO), are now promising materials capable of molecular and ionic sieving [57]. The study by Ren et al. was the first report regarding MXene-based water treatment membrane, where vacuum-assisted filtration method used to produce the membranes, in which A membranes made of 2D $\text{Ti}_3\text{C}_2\text{T}_x$ MXene nanosheets was put together. Traditionally, MXenes are adjusted with a high hydrophilicity because the flow of GO membranes is relatively minimal underneath the interlayer spacing pressure. $\text{Ti}_3\text{C}_2\text{T}_x$ permits interlayer H_2O , which is more conducive to rapid water flow than GO [58, 59]. Additional research has shown that 2D $\text{Ti}_3\text{C}_2\text{T}_x$ MXene enhanced with Ag nanoparticles has an ultrafast water treatment

membrane [60]. Another problem for MXene-based adsorbent materials and barriers is the targeted adsorption/isolation of hazardous species, which necessitates engineering-focused experimental approaches.

6.3 | Antimicrobial Applications of MXenes in Water Treatment

Antimicrobial activities are possible using MXene in aqueous media. The antimicrobial activity of MXenes is not just contingent on size but also on exposure period, according to research by Gogotsi et al. [61, 62]. Researchers also demonstrated the usefulness of MXenes as effective antibacterial coatings. The aging $\text{Ti}_3\text{C}_2\text{T}_x$ barriers that have been successfully employed to reduce *E. coli* accumulation display more pronounced bacterial development suppression than fresh ones in the implementation [58].

It is significant to highlight that a variety of variables, including nanosheet geometry, delamination level, lateral width, amount of layers, surface chemistry (modification), number of surface defects, and aggregating, may influence the antibacterial activity of 2D nanomaterials. The MXene-modified membrane has shown antibacterial property in testing, making it appropriate for filtering air including bacteria and a prospective option for the design of advanced filtration equipment, particularly in the area of biomedicine [58].

7 | Enhanced Bioimaging

MXenes have several biocompatible properties which render them very useful for biomedical applications. A summary is shown in Figure 15. Cancer is a deadly disease and one of the most major threats to human life. There are various traditional surgical treatment procedures that cause large wounds to the body. There is chemotherapy, which not only kills the cancer cells but also the healthy cells. Besides all these, recently photothermal therapy has been developed where the tumor cells absorb near infrared light and convert it to heat which destroys the cells. MXenes have been extensively studied for photothermal treatment of tumors. Also, they have been used as a contrast agent for bioimaging. As contrast agents, the tumor location can be seen in real-time through bioimaging. MXenes were grown on MnO_x nanoparticles usually in situ on the reduced surface for nanosheets which are used as a contrast agent for contrast-enhanced CT.

Huang et al. reported that Ti_3C_2 MXenes have a prominent feature of absorbing light at the UV range and have been used as laser-generated ultrasound imaging contrast agents, showing the potential for diagnosis, monitoring during treatment, and image guidance. They serve as a high-performance contrast agent. This shows that MXenes can monitor lesions while achieving synergetic treatment. They have also been confirmed to have good electrical properties and conductive insulation [59].

Graphene quantum dots (GQDs) using Ti_3C_2 MXenes are very effective and a prominent candidate as reported by Li Zhou et al. They are rich in functional groups, have stable optical properties, and are soluble in water and most organic solvents. They

TABLE 1 | MXenes and their usage for environmental applications.

Photocatalysis	Pollutant	Experimental conditions	Efficiency (%)	Key inferences	Ref
ZnO/Ti ₃ C ₂ T _x	RhB	Co = 10 mg/L Dosage = 0.7 g/L 500 W Xe arc lamp	98 (80 min)	Performance was enhanced primarily due to the improved surface area and decreased resistance of transmitting photoinduced charge carriers.	[47]
Magnetic-Ti ₃ C ₂ T _x	Diclofenac	Co = 10 mg/L Dosage = 3 g/L 20-W Hg lamp	100 (30 min)	The magnetic-Ti ₃ C ₂ T _x exhibited superior stability for seven continuous cycles.	[48]
Fe ₃ O ₄ /Ti ₃ C ₂	MO MB CR RhB	Co = 10 mg/L Dosage = 0.5 g/L pH 3	MO = 100 MB = 100 CR = 98 RhB = 100 within 14 min	The chemical reactions implicated in the photocatalysis process were indicated to be •OH and O ₂ •- by the revolutionary scavenger research and electron paramagnetic resonance investigation.	[49]
g-C ₃ N ₄ /Ti ₃ C ₂	Ciprofloxacin	Co = 20 mg/L Dosage = 0.2 g/L 500-W Xe lamp	100 within 150 min	Ti ₃ C ₂ and g-C ₃ N ₄ created a Schottky junction, whereby prevented the crossover linking of electron-hole pairs.	[50]
CeO ₂ /Ti ₃ C ₂	TC	Co = 10 mg/L Dosage = 1 g/L 300-W Xe lamp	78.83 within 60 min	The Schottky connection between CeO ₂ and Ti ₃ C ₂ , which transfers the photoexcited electrons from CeO ₂ to Ti ₃ C ₂ , was attributed with the improved efficiency of CeO ₂ /Ti ₃ C ₂ .	[51]
CuO/BCN/ MXene	Malachite green, TOC in refractory effluent	Refractory pollutants (50 mg/50 mL) under sunlight, MG 0.5, 1.0, 1.5, and 2.0 g/L	98.3% of MG dye and 75% TOC removal within 120 min	Transmission between CuO and BCN nanosheets sped up.	[52]
Ti ₃ C ₂ -MXene	Methylene blue	0.0015 g of photocatalyst in 30 mL of a 10-ppm MB electrolyte.	49.60% within 4 h	Efficient charge separation through the Schottky junction at the TiO ₂ -MXene interface	[53]

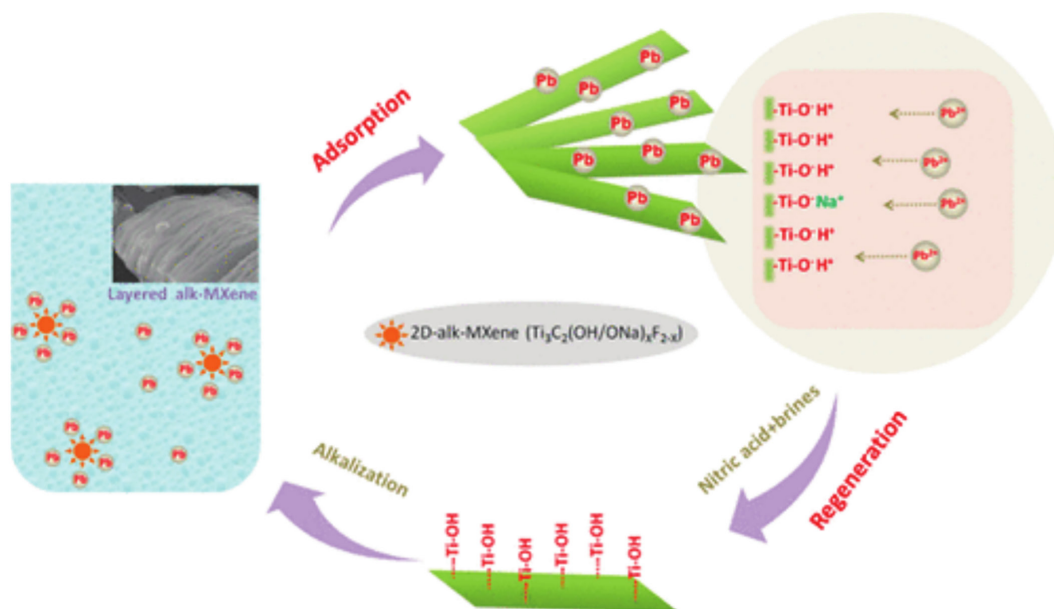


FIGURE 14 | MXene-based removal of lead through adsorption/regeneration [55].



FIGURE 15 | Biomedical applications of MXenes based on their unique properties [59].

are used in various optical applications such as fluorescent ink, light-emitting composites, and bioimaging. A new way of cutting C-metal bonds to afford GQDs or fluorescent carbide-derived carbons could be applied to other layered MXene materials; thus, this work opens a brand new and intriguing direction for the creation of luminous carbon nanoparticles. A multilayer MXene was formed by sonification process (Figure 16a). The multilayer MXene showed excellent dispersity in DMF and the transmission electron microscope (TEM) images showed that single- or few-layers Ti₃C₂T_x flakes with lateral sizes ranging from hundreds of nanometers to several micrometers were formed (Figure 16b). TEM images indicate that the sizes of

as-made GQDs are in the range of 4–10 nm (Figure 16c). The AFM images and corresponding height analysis reveal a topographic height, indicating that the majority of GQDs have two graphene layers (Figure 16d) [60].

Feng et al. [61] have reported 2D Mo₂C MXenes as phototherapeutic agents for photonic tumor hyperthermia. Mo₂C was obtained by removing Ga from the non-MAX phase Mo₂Ga₂C. Also, the features of molybdenum-based MXenes for in vivo treatment, including biocompatibility, toxicity, and biodegradability, have not explicitly been studied, and there have been limited investigations regarding their use for cancer therapy.

As MXenes have a great role in their magnetic property, they have been an outstanding contrast agent for bioimaging. The 2D nanosheets exhibit various physicochemical properties such as the effects of quantum size, intrinsic photothermal performance, effective loading of functional contrast agents, and element-enhanced contrast, which improves the imaging performance [62, 63]. Contrast-based imaging can locate the tumor and guide photothermal treatment, which also includes photoacoustic imaging (PAI), magnetic resonance imaging (MRI), X-ray computed tomography (CT), and luminescence imaging [64–67]. All these have significantly increased the success rate of cancer treatment.

8 | Anticancer Applications

MXenes have such exciting physical and chemical properties that they have been emerging rapidly as the most versatile nanomaterials. Also, the good biocompatibility property, optical properties, and tunable electronics have made MXenes reach the cancer theranostics. Most of the MXenes in cancer applications are titanium based. MXenes-based photothermal tumor eradication on NIR-I and NIR-II bio windows and also multiple imaging-guided photothermal tumor ablation [68, 69] showed that this method involved local heating effect to eliminate the tumor with poorly vascularized microenvironment. MXenes

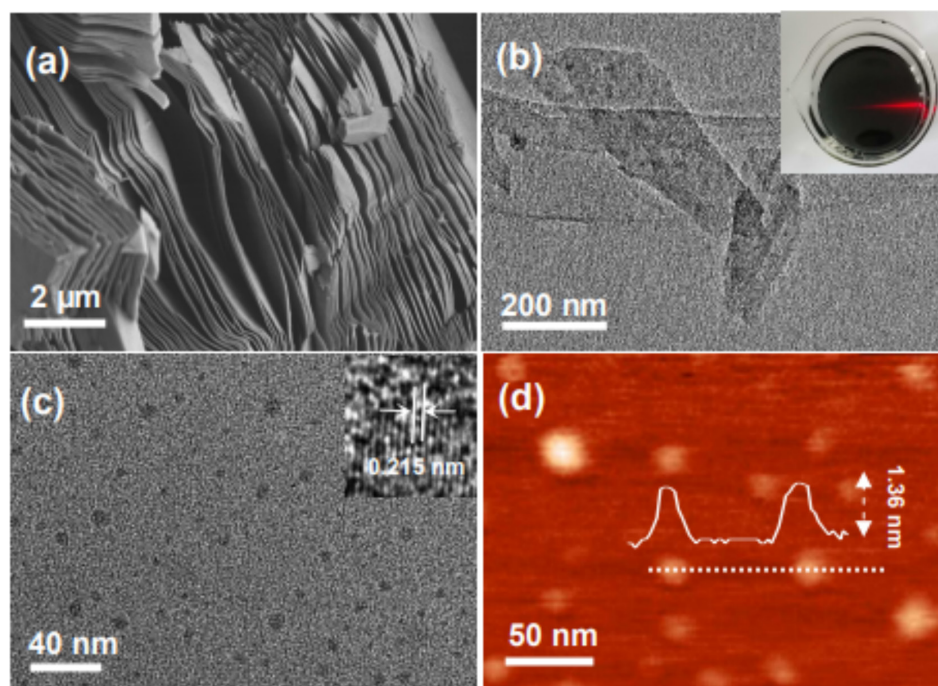


FIGURE 16 | (a) SEM representation of the multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. Representative TEM images of delaminated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene (b) and GQDs (c), insets of (b) and (c) are the representation of delaminated $\text{Ti}_3\text{C}_2\text{T}_x$ MXene in DMF and TEM image of GQDs, respectively. (d) AFM representation of the GQDs, inset of (d) is the respective length profile along the dashed line [60].

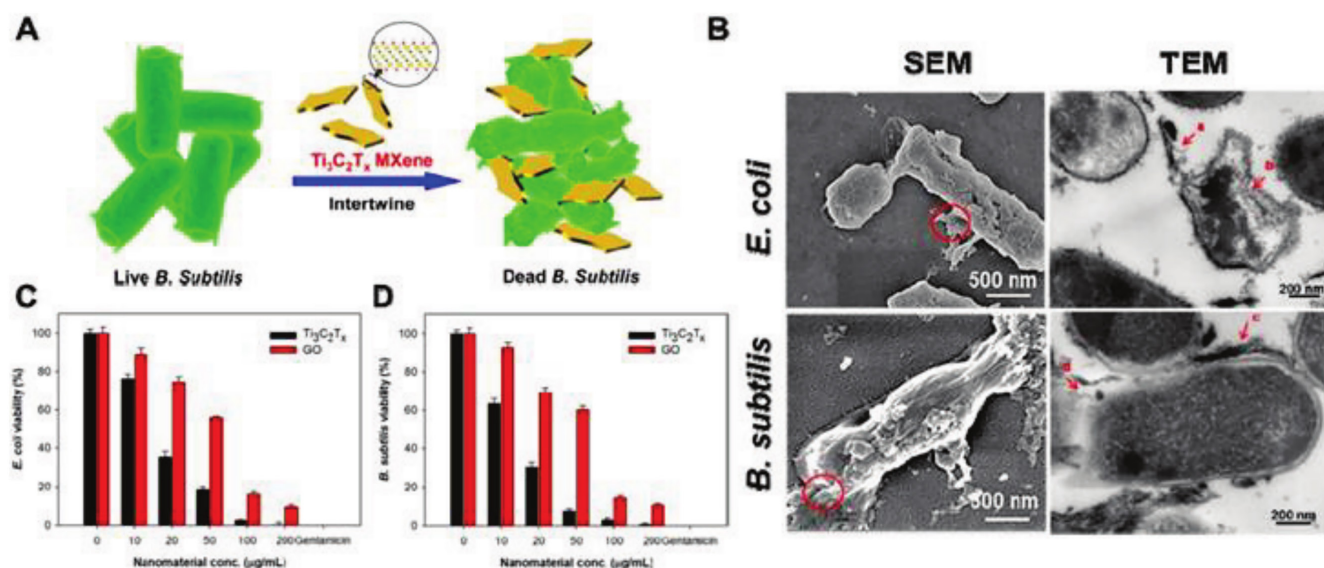


FIGURE 17 | Antimicrobial properties of MXenes [71].

that make use of the reactive metal-F pairs are used in photothermal antibacterial which is an approach to destroy and kill bacteria by production of heat when exposed to light at the right power density as shown in Figure 17 [29, 68, 70].

The photodynamic compounds in titanium carbide sheets are effective versus murine breast cancer cells. By providing an additional A13+ to complement A1 loss, ultrathin Ti_3C_2 MXenes nanosheets with a size of about 100nm were shown to be effective as a photothermal/photodynamic agent for the treatment of cancer [8]. A Ti_3C_2 -based composite MXene system ($\text{MnOx}/$

Ti_3C_2) that is effective for magnetic resonance (MR) and photoacoustic (PA) dual-modality imaging-guided photothermal treatment may be used as a multipurpose cancer theranostic technology (PTT). The TEM images of Ti_3C_2 MXenes are given in Figure 18 [72]. MXenes for therapeutic application. A. Intravenous infusion, phase-changeable PLGA/ Ti_3C_2 implants were administered into the tumor together with Ti_3C_2 -SP nanomaterials. B. Following intravenous injection, the Ti_3C_2 -SP nanosheets reached and aggregated at tumor tissues via the EPR effect. C. When Ti_3C_2 -SP is subjected to an NIR laser, cancer cells are photothermally ablated [73, 74].

MnOx/Ti₃C₂ is used in effective tumor ablation and growth suppression. MXenes have produced promising results toward specific types of cancers and strategies.

9 | Toxicology of MXenes

Accelerating the use of 2D components in the production of biomedical engineering, its toxicology aspects should be considered. Among the 2D materials employed in technical applications with the biggest potential is MXene. Various studies showed the various differences in toxicological effects in view of MXenes stoichiometry. Also, cytotoxicity was also analyzed with respect to the number of layers constituting MXenes [73]. Analysis of MXenes for biological studies is very time consuming and costly. And many certification procedures should be done for the safety of commercial products that contains nanomaterials. Due to the low toxicity of MXenes, the material is used for PDT-based

tumor hyperthermia as shown in Figure 19. There is significant need to overcome the problems of this analysis [75–77].

Machine learning (ML) is one of the best methods to cytotoxicity studies for various chemicals and also to predict the synthesis of MXenes. MXenes however exhibit low toxicity and good biocompatibility as shown in Figure 20 [78]. The stability of MXenes is taken into account during toxicity evaluation. But they have been proven to be harmful to embryos and stem cells. The substance dosage, cell type, exposure route, and particular MXene type are all linked to the harmful consequences in both vitro and in vivo. Additionally, the surface alterations change how toxic MXenes are [79, 80].

Graphene-based MXenes are used in various biomedical applications. The exposure to these materials makes them viable to a degree on cytotoxicity and biocompatibility. The cytotoxic effects mostly depend upon their physical and chemical characteristics,

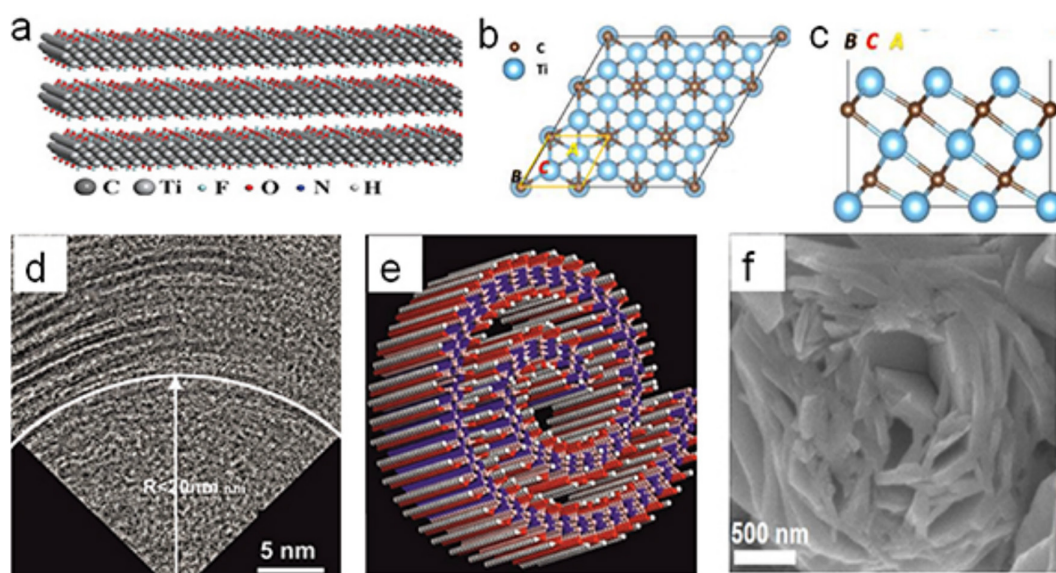


FIGURE 18 | Schematic of Ti₃C₄ monolayer, (a) schematic, (b) top, (c) side, (d) TEM image, (e) schematic, and (f) SEM image of the MXene flower [72].

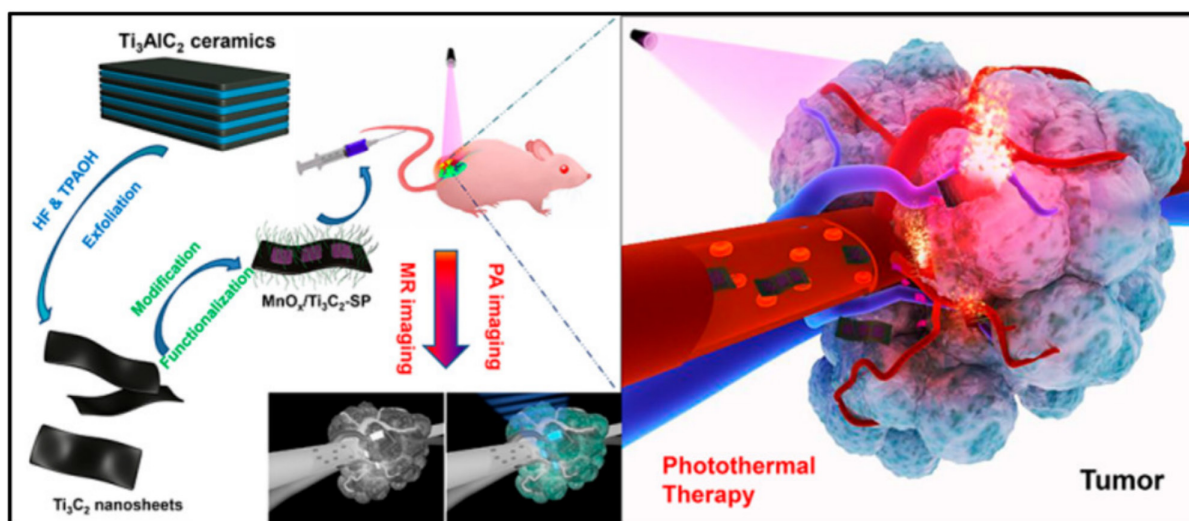


FIGURE 19 | PDT-based treatment using MXenes [75].

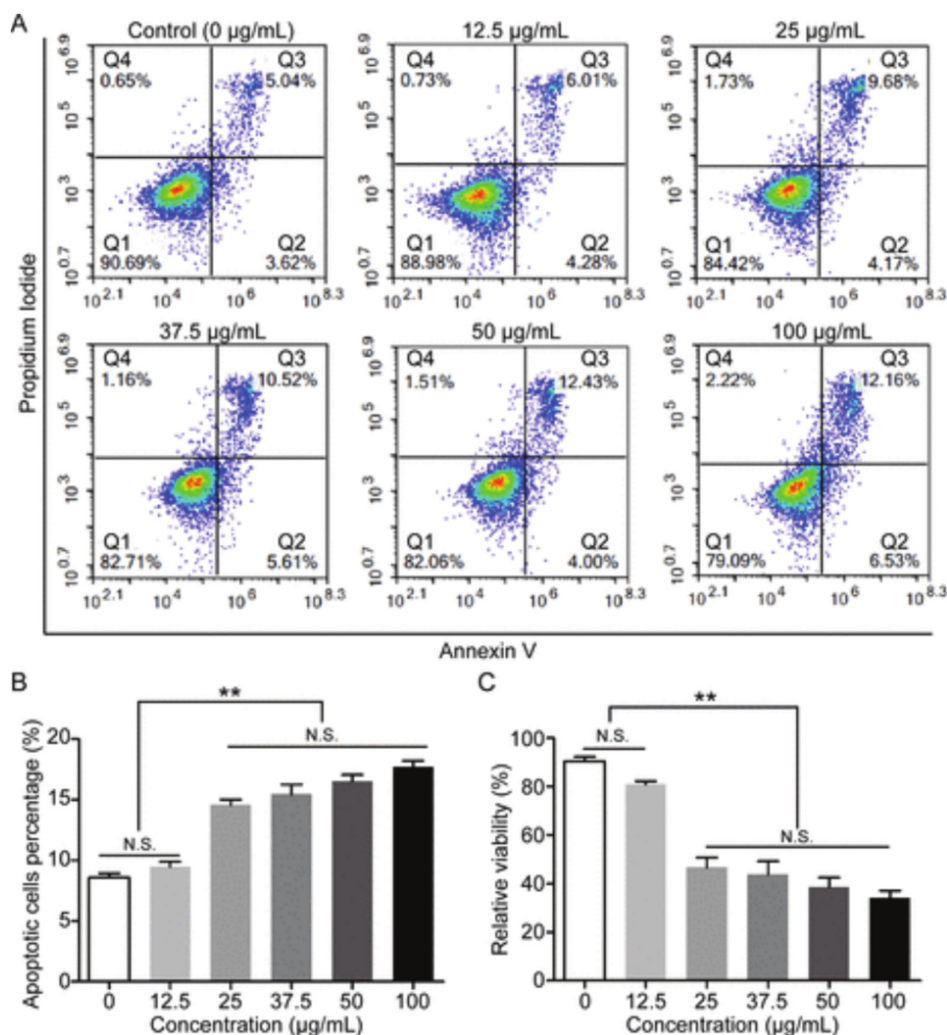


FIGURE 20 | Representative image of neural stem cells interaction with Ti_3C_2 MXenes and its toxicity analysis through flow cytometry [78].

the manner in which they interface with cells, as well as the fact that they accumulate in certain structures and organs, as indicated by Tabish et al. [81]. The existence of graphene has the greatest impact on the toxicological consequences of nanocomposites, and a thorough study of their biological and molecular connections with human cells, tissues, and organs is required to comprehend their impacts. The cytotoxicity of Ti_3C_2 is studied widely by using primary neural stem cells (NSCs) and NSCs-derived differentiated cells in terms of apoptosis, viability, cellular uptake, cell membrane integrity, and global gene expression profiles [79, 80, 82].

9.1 | Other Applications

MXenes are a family of 2D transition metal carbides, nitrides, or carbonitrides that have garnered significant interest due to their unique properties such as high electrical conductivity, mechanical strength, hydrophilicity, and tunable surface chemistry. These properties enable MXenes to be used across a wide range of applications,

- **Thermoelectric**—MXenes can be engineered for thermoelectric energy conversion, where heat is directly converted into electricity, potentially useful for waste heat recovery [80].

- **Tribology and lubricants**—As solid or additive lubricants, MXenes reduce friction and wear in mechanical systems due to their layered structure and low shear strength [81].
- **Neuromorphic computing**—MXenes are being studied in memristors and artificial synapses to emulate synaptic behavior in neuromorphic (brain-inspired) systems [83].
- **Antimicrobial and antiviral coatings**—Their surface properties and reactive terminations enable MXenes to act as antimicrobial agents or coatings on medical devices and surfaces [84].
- **Photodetectors and optoelectronics**—Some MXenes exhibit strong light-matter interaction suitable for photodetectors, modulators, and other optoelectronic devices [85].
- **Fire retardants**—MXenes can be incorporated into polymers or textiles to improve thermal stability and act as flame retardants [86].
- **Hydrogen storage**—MXenes are candidates for reversible hydrogen storage materials due to their surface terminations and high surface area [87].
- **Smart textiles**—Integrated into fabrics for temperature regulation, EMI shielding, or health monitoring, combining flexibility with high performance [88].

- Actuators and soft robotics—Their responsiveness to electrical and thermal stimuli makes them useful in soft actuators for robotics or adaptive materials [89].
- 3D printing and additive manufacturing—MXenes can be dispersed in inks and resins for 3D printing conductive or functional components [90].

10 | Conclusions

The highly ordered, tunable, and robust framework of MXenes makes them an adequate scaffold candidate for transplantation for augmenting bio-reactive molecules. Those three basic factors are involved in tissue engineering. Due to their photoreactive behavior, MXenes have the potential to be highly effective in targeted cancer photodynamic therapy. The cancer cell must internalize photothermal agents for them to be most effective, and MXenes can be delaminated to be in nanodimensional flakes for cellular uptake. The use of MXenes in controlled or external stimuli-responsive drug delivery to specific areas of interest increases the carried drug's bioavailability. Due to their highly stable behavior in a variety of conditions, MXenes are worthy candidates to be considered in various biological and environmental applications. The materials are highly ordered and hence present the possibility of controlled adsorption of contaminants, microbial pathogens, which can be engaged in membranes for water and air filtration devices. Thus, with their unique properties, excellent stability, and precise tunability, MXenes are ideal candidates for the improvements in various applications along with appropriate fabrication strategy and choice of composite materials. Numerous applications, including as medication delivery, bioimaging, cancer treatment, and biosensing, are being researched for MXenes. They are perfect candidates for precision drug delivery systems because their surface functionalization enables the selective targeting of particular cells. Additionally, by serving as carriers for therapeutic compounds or as agents for photothermal therapy, MXenes' biocompatibility and ease of functionalization with biomolecules increase their potential in bioimaging and cancer treatment. Because of their large surface area, which makes it possible to detect biomarkers at low concentrations with efficiency, MXenes are also being investigated as biosensors. MXenes are equally promising in the environmental sector, particularly in water purification and pollution control. Their large surface area and surface chemistry enable effective adsorption and removal of heavy metals, organic contaminants, and even salts from water. Additionally, MXenes have shown potential in catalytic applications, such as the degradation of harmful pollutants, making them valuable in addressing environmental concerns. Their use in energy-efficient filtration systems further enhances their role in sustainable water treatment processes.

11 | Challenges and Future Prospects

Despite the exciting potential, challenges such as the scalability of MXene production, long-term stability, and potential toxicity in biological systems remain. Researchers continue to address these concerns by focusing on improving the synthesis techniques and functionalizing MXenes for enhanced

biocompatibility and environmental sustainability. Overall, the review emphasizes that MXenes, with their unique properties, hold great promise for advancing both biomedical and environmental technologies, but further research is required to fully realize their potential in real-world applications.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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