Research Article

Journal of
Environmental
Nanotechnology

MXene-based Nanobiosensors for Environmental Pollutant Detection: Recent Advances, Challenges and Future Perspectives

R. Indhumathi[1*], R. Saranya[2], V. Monika[2] and Divyadharshini Mani[3]
[1]Department of Biomedical Engineering, SRM Institute of Science and Technology, Ramapuram Campus, Chennai, TN, India
[2]Department of Biotechnology, SRM Institute of Science and Technology, Ramapuram Campus, Chennai, TN, India
[3]Institute of Biomedical Technology, Karlsruhe Institute of Technology, Institute of Biomedical Technology, Karlsruhe, Germany
Received: 18.06.2026 Accepted: 16.07.2026 Published: xx.xx.xxxx
*indhumar1@srmist.edu.in

ABSTRACT

MXenes have appeared as a potential variety of two-dimensional materials for environmental biosensing due to their remarkable conductivity, flexible surface chemistry, and large surface area. This article presents an analytical review based on published works covering the last ten years, though it goes beyond previous analyses in scope. This paper takes an integrated approach to the synthesis of MXenes, as well as their surface modifications, biosensing methods, applications of MXenes to environmental monitoring, challenges of commercializing MXenes, and possible areas for future studies. Studies in the literature show that MXene-based nanobiosensors provide superior performance in terms of enhanced sensitivity and selectivity as well as fast responses in detecting various environmental pollutants such as metals, pesticides, microorganisms, drugs, and new organic substances. Additionally, it discusses the effect of synthesis and surface modification on the efficiency of sensors for different applications in environmental monitoring.

There are various critical challenges hindering the successful use of MXene-based nanobiosensors in practice. These cover issues such as degradation due to oxidation, low reproducibility, difficulties related to large-scale manufacturing, lack of standardized and regulated fabrication processes, as well as lack of toxicity testing over longer periods of time, which presents hurdles for commercialization and adoption of these devices in practice. All these aspects are discussed in detail in relation to practical environmental monitoring with the aim of identifying gaps in knowledge and technology. Future studies need to focus on achieving the development of oxidation-resistant MXenes, methods of sustainable synthesis, standardized production processes, large-scale manufacturing approaches, and complete environmental safety assessments. Solving these issues will allow MXenes-based nanobiosensors to emerge from the laboratory setup and be used in environmental monitoring in practice.

Keywords: MXenes; Nanobiosensors; Environmental sensing; Electrochemical biosensors; Surface functionalization; Environmental pollutant detection; Two-dimensional materials; Biosensing.

1. INTRODUCTION

Environmental pollution is a serious global issue that has emerged as a result of rapid industrial development, an increase in urbanization, continued increase in population growth and increases in productive agricultural activities. The continued release of these chemicals and toxins, for example, mercury (Hg^{2+}), lead (Pb^{2+}), cadmium (Cd^{2+}), arsenic (As^{3+}) and many others into our water, soil and air has had a dire impact on both the ecosystems of our world as well as on the overall health and well-being of human beings (Kaul, 2013). The heavy metals shown above, even in small amounts, are considered very toxic and are readily taken into biological systems, where they will accumulate and become a source of serious damage/disruption to neurological, renal and carcinogenic functions/systems in human beings (Fuhrer et al., 2010). We also have a large amount of pesticides and pharmaceuticals that will remain in the environment and be distributed into different areas of the environment for long periods of time, posing ecological as well as toxicological threats to the health and welfare of our global community, thereby creating the need for the continued development of rapid, sensitive and reliable technologies for the detection and monitoring of environmental pollutants (Ali *et al.* 2024a). This paper will focus on MXene nanobiosensors for biological pollutants, which include heavy metals, pesticides, drugs, microorganisms, endocrine disruptors, dyes, and medicines present in water, soil, and air (Yoon *et al*. 2020; Zhang *et al.* 2017). The choice of pollutants was made based on the distribution, durability, and harmful impact on nature and human beings (Novoselov *et al.* 2007; Pillai *et al.* 2023).

The field of biosensing systems has undergone significant changes with the use of nanotechnology in biosensing systems; this has resulted in the creation of nanobiosensors that can detect analytes more effectively than other types of biosensors (Fan *et al.* 2021). A large variety of nanomaterials have been examined for use in biosensor manufacturing, but two-dimensional (2D) materials have generated great interest among biosensor researchers due to their unique structural and electronic properties (Anasori *et al.* 2020; Fan *et al.* 2022).

MXenes are a growing class of two-dimensional transition metal carbides, nitrides and carbonitrides that have been the focus of intense interest over the last few years in the fields of biosensing and environmental applications (Ali *et al.* 2024b). MXenes have displayed many impressive physicochemical characteristics, including metallic conductivity, hydrophilicity, tunable surface chemistry, high interlayer spacing and very good mechanical flexibility. These properties render MXenes excellent candidate materials for electrochemical and optical sensing devices (Feng *et al.* 2020b).

MXenes are different from other two-dimensional materials, including graphene, MoS_2, black phosphorus, and g-C_3N_4. The major advantages of MXenes are their exceptional transport characteristics, hydrophilic properties, and the abundance of surface functional groups that allow changing surface chemistry, making MXenes a compelling candidate for electrochemical biosensing. However, MXenes are also more prone to oxidation than graphene, black phosphorus possesses poor stability in ambient conditions, and MoS_2 has low conductivity. In this context, it is worth noting that each material has some merits and drawbacks depending on the required sensing application (Deng *et al.* 2020).

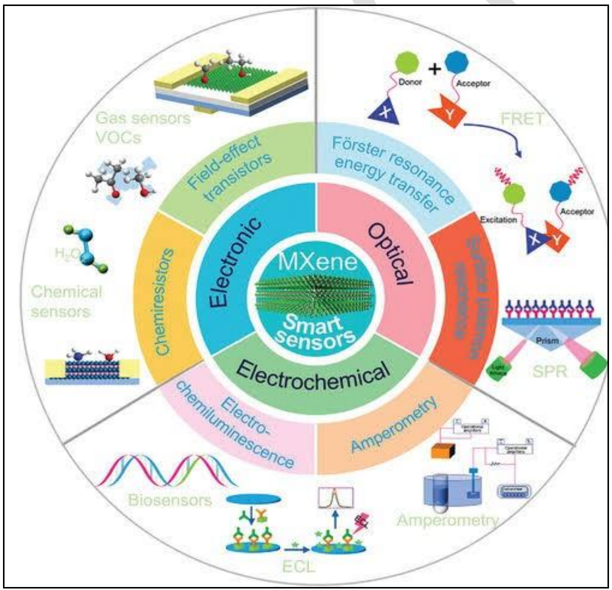

Fig. 1: MXene composite-based electrochemical biosensing platform incorporating biological recognition elements and functional nanomaterials

The MXene composite-based electrochemical biosensing system is generally depicted as shown in Figure 1, where MXene nanomaterials have been incorporated with biological recognition factors, functional nanomaterials, and the electrochemical transducer for environmentally acceptable pollutants' detection. The diagram shows the overall details of the signal transduction process together with the unique contribution of the components of the System. It is important to note that, although MXene-based nanobiosensors exhibited great performance in laboratory tests, many obstacles still exist in their practical application. Particularly challenging is the achievement of long-term operational stability, which is affected by corrosion and environmental factors. It is necessary to overcome these issues with the use of more advanced material engineering techniques, uniform production methods, and a proper level of verification of the devices in real-life conditions (Askari *et al.* 2025).

Although MXenes are known to have excellent sensing abilities, there are still important limitations that are preventing MXene-based nanobiosensors from being used at large scales. Most MXenes are highly vulnerable to oxidation under ambient conditions, which gradually leads to their deterioration in conductivity and sensing ability during storage and operation (Mirkhani *et al.* 2019). In addition to those drawbacks, large-scale synthesis, consistent surface terminations, variations from batch to batch, durability during operations, biofouling in complex environmental media, and production costs are still among the main challenges that must be met in order to continue the use of MXene-based nanobiosensors in practice. Issues of environmental safety, long-term biocompatibility and necessary regulatory approval should also be solved in order to use nanobiosensors on a commercial level (Li *et al.* 2022).

MXenes are increasingly of interest for detecting pathogens and emerging contaminants, including pathogens that infect people through contaminated water (e.g., bacteria, viruses, fungi), and for rapidly developing sensing technologies. Conventional methods for detecting bacteria or other microbes in water can be labor-intensive and may take a long time to produce results (Hao *et al.* 2022). This increases the need for rapid sensing platforms. MXene-based biosensors have excellent promise for detecting microbial contamination by electrochemical, fluorescence, and colorimetric approaches. MXene-based biosensors also show great potential for detecting pharmaceutical residues, antibiotics, hormones, and microplastics that are present in the environment (Tripathy and Pradhan, 2026; Hajian *et al.* 2022).

The aim of this article is to present a detailed evaluation of the latest achievements related to MXene nanobiosensors used for environmental pollution detection (Xin *et al.* 2020). The article contains a description of methods of MXene synthesis, its physical and chemical properties, methods of surface modification, mechanisms of biosensing, classification of the sensors, and areas of application for detection of heavy metals, pesticides, medicines, pathogenic organisms, and new types of pollution (Guo *et al.* 2020). We have paid special attention to such aspects as the quantitative characteristics of the sensors, comparison with the other two-dimensional nanomaterials, resistance against oxidation, replicability, problems with commercialization, and verification in real life. The final part of the article considers promising directions of research (Tu *et al.* 2018).

The present review is different from previous review articles as it focuses on the various MXene-based nanobiosensors and highlights the important aspects of MXene technology for environmental monitoring purposes. It combines information about synthesis pathways, surface modification, the working principles of different sensors, performance results in terms of analytical measurements, applications in environmental monitoring, drawbacks in the commercialization of MXenes, governmental issues arising during the use of MXenes, and possible future development of MXenes. Even though numerous review papers have released some information about MXene biosensors, there is no full review that summarizes the synthesis, surface modification, sensing mechanisms, detection of environmental contaminants, commercialization hurdles, and legislative aspects influencing these sensors. This review aims to fill in the gap by providing a comprehensive and critical analysis of the above-mentioned interrelated areas needed for the development of new MXene-based sensor technologies.

2. STRUCTURE AND PROPERTIES OF MXENES

MXene is a broad term for numerous types of metal carbides, nitrides, and carbonitrides, which can be represented with the common formula $M_{n+1}X_nT_x$, where M stands for transition metals (Ti, V, Nb, and Mo), X can be carbon, nitrogen, or both, and T can refer to surface groups (-OH, -O, -F) (Wang *et al.* 2019). The synthesis of MXenes occurs mainly through a selective etching of the "A" element in the MAX phases ($M_{n+1}AX_n$), which leads to the formation of unique ultrathin nanosheets with valuable properties useful in many fields of applications like catalysis, energy storage, medical sciences, and environmental sensing (Rajavel *et al.* 2020; Feng *et al.* 2020a). Moreover, the materials with hydrophilic surface functional groups (–OH, –O, and –F) easily disperse in water and allow strong interaction with various biomolecules, such as enzymes, antibodies, aptamers, and nucleic acids, without losing their biological activity (Liu *et al.* 2019; Roy *et al.* 2013).

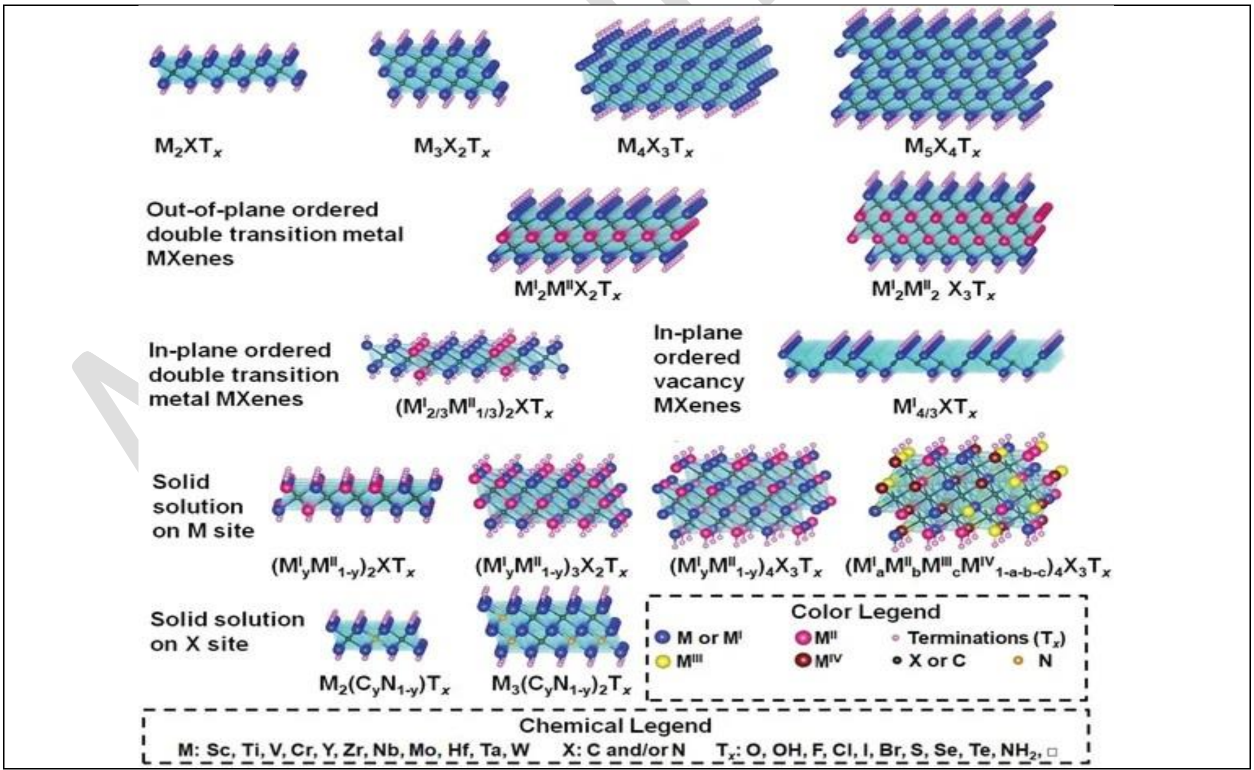

Fig. 2: Illustration of MXene structural classification. The structural types shown here are the classical types of MXene (M_2XT_x, $M_3X_2T_x$, $M_4X_3T_x$, and $M_5X_4T_x$), double transition metal MXenes with out-of-plane and in-plane orderings, and vacancy-ordered i-MXenes, along with solid-solution MXenes

Table 1. Comparison of different MXene compositions and their typical environmental applications

MXene Composition	Electrical Conductivity	Oxidation Stability	Surface Functionalization	Major Advantages	Limitations	Typical Environmental Sensing Applications
$Ti_3C_2T_x$	Excellent (~10,000 S cm^{-1})	Low	Excellent due to abundant –OH, –O and –F terminations	High electron transfer rate, large surface area, easy biomolecule immobilization	Poor long-term stability; oxidation reduces conductivity	Heavy metals (Pb^{2+}, Hg^{2+}), pesticides, antibiotics, pathogens, phenolic compounds
Nb_2CT_x	High	Moderate to High	Good	Better chemical stability, improved corrosion resistance, good electrochemical activity	Lower conductivity than $Ti_3C_2T_x$; fewer biosensing reports	Gas sensing, heavy metal detection, electrochemical environmental sensors
V_2CT_x	Moderate to High	Moderate	Good	Excellent catalytic activity and redox behavior	Difficult synthesis, limited availability, lower stability than Nb_2CT_x	Electrochemical detection of pollutants, catalytic sensing applications
Mo_2CT_x	High	High	Moderate	Superior catalytic activity, excellent oxidation resistance, enhanced optical properties	High synthesis cost and limited large-scale production	Optical biosensors, photocatalytic sensing, environmental pollutant monitoring

2.1 Important Physicochemical Properties of MXenes

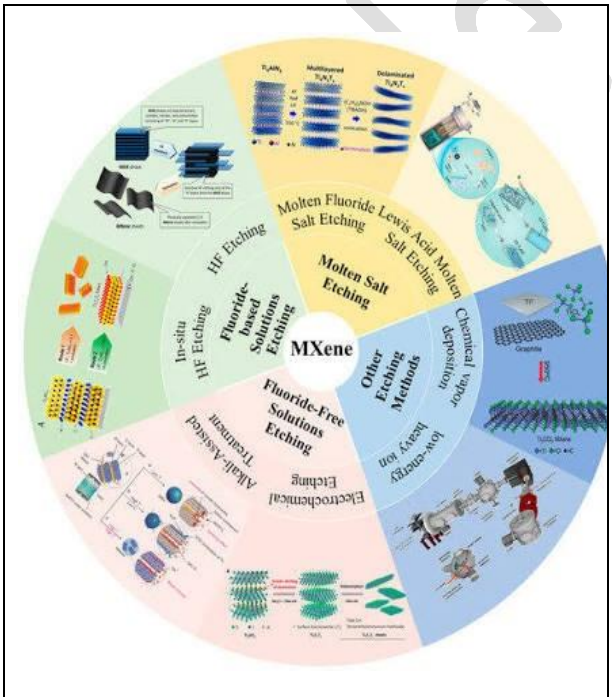

Fig. 3: Synthesis methods of MXenes: top-down method and bottom-up technique, diagrams of two main processes of MXene synthesis, the top-down technique includes selective etching of MAX phases and delamination, the bottom-up method makes use of the growth process such as chemical vapor deposition, the techniques will affect the composition, structure, and surface properties of MXenes for applications

The other important advantage of MXenes is their mechanical flexibility and structural robustness (Sarycheva and Gogotsi, 2020). Due to their flexible layered structure, they can be manufactured into wearable, flexible and portable sensing devices for real-time monitoring of the environment. MXenes also have good mechanical strength, enabling the durability and operational stability of the sensor platforms. Therefore, these properties are crucial for developing flexible environmental sensors and smart monitoring devices (Naguib *et al.* 2021).

There exist several forms of atomic groups, referred to as MXenes, that provide MXenes with distinctive properties that will determine their electrochemical/Physicochemical/mechanical behaviour. The functional groups of MXenes, such as -OH, -O, and -F, will influence MXenes' conductivity, catalytic activity, hydrophilicity, and biomolecule interactions. Thus, chemically modifying MXenes or developing hybrid nanocomposites will improve how efficiently MXenes can detect target pollutants and significantly increase the selectivity of those detections by tailoring the electronic structures of MXenes for precise electrochemical and optical sensing of each of these target pollutants.

Although MXenes have many advantages, the production of MXenes on a large-scale has been limited by scalability challenges. One challenge to the widespread use of MXenes is the fact that MXenes are highly susceptible to oxidation under standard atmospheric conditions, which destroys their structure, conductivity, and detection ability. To overcome the limitations imposed by oxidation at scale, researchers have conducted investigations into stabilisation methods for MXenes, including using antioxidants, low temperature storage/storage, polymer encapsulation, and hybrid nanocomposite formation.

In recent years, MXenes have demonstrated remarkable potential in environmental sensing applications due to their unique combination of conductivity, hydrophilicity, large surface area, tunable surface chemistry, and biocompatibility. These properties have enabled the development of highly sensitive and selective nanobiosensors for detecting heavy metals, pesticides, pathogens, pharmaceutical contaminants, and emerging pollutants in water, soil, and air. Consequently, MXenes continue to attract growing interest as advanced functional nanomaterials for next-generation environmental monitoring technologies (Ayodhya, 2023).

This table provides a comparison between MXenes, graphene, MoS_2, black phosphorus, and g-C_3N_4 on various parameters like electrical conductivity, surface functionalization, resistance to oxidation, catalytic activity, sensing performance, and other major drawbacks. Also, a thorough evaluation of MXenes and other materials has been provided. This review has pointed out that MXenes are an advanced material and can replace other materials in environmental biosensing applications, even though they have some issues with oxidation resistance and commercialization on a large scale.

Table 2. Comparative Properties and Environmental Sensing Applications of MXenes and Other 2D Nanomaterials

Material	Electrical Conductivity	Surface Functionalization	Oxidation Stability	Major Advantages	Major Limitations	Typical Environmental Sensing Applications
MXenes	Excellent	Excellent (–OH, –O, –F terminations)	Moderate to Low	High conductivity, rapid electron transfer, hydrophilic surface, easy biomolecule immobilization	Oxidation, limited large-scale production	Heavy metals, pesticides, antibiotics, pathogens
Graphene	Excellent	Limited (requires chemical modification)	Excellent	High carrier mobility, mechanical strength, excellent stability	Low catalytic activity, poor hydrophilicity	Electrochemical sensors, gas sensors
MoS_2	Moderate	Good	Good	High catalytic activity, semiconducting behavior, abundant active edge sites	Lower conductivity than MXenes	Heavy metal and gas sensing
Black Phosphorus (BP)	High	Moderate	Poor	High carrier mobility, tunable band gap, excellent sensitivity	Rapid oxidation under ambient conditions	Optical and electrochemical biosensors
g-C_3N_4	Low to Moderate	Excellent	Excellent	Good chemical stability, photocatalytic activity, low cost	Low electrical conductivity	Photocatalytic sensing, organic pollutant detection

Graphene, despite being one of the most used two-dimensional materials because of its unique electrical conductivity and mechanical strength, possesses a chemically inert surface and therefore often requires additional functionalization to achieve better biomolecule immobilization and sensing efficiency. MoS_2 has better catalytic activity due to the presence of many active edge sites, yet its comparatively lower conductivity does not provide fast electron transfer. Black phosphorus exhibits exceptional charge transfer characteristics and high sensitivity, but it also undergoes rapid oxidation, which limits its use. On the contrary, g-C_3N_4 shows excellent chemical durability and photocatalytic activity but has low intrinsic conductivity. MXenes possess a number of advantages, including the presence of metallic conductivity, a hydrophilic surface, the availability of functional groups on the surface, and biocompatibility, making it possible to achieve efficient immobilization of biomolecules and effective electron transfer. However, susceptibility to oxidation, long-term preservation, and production technology prove to be a significant challenge that needs to be solved before the technology can be used. Thus, the choice of a proper two-dimensional material should depend on the use of the specific sensor in the context of conductivity, stability, activity, and complexity of production.

2.2 Synthesis Methods of MXenes

MXene production involves etching element A from the MAX phase crystalline material selectively, leaving the other elements (transition metal and carbide or nitride) intact. MAX phases have the following formula $M_{n+1} A X_n$, where M is an early transition metal, A is an element located in Group 13 or 14 of the periodic table, and X is carbon, nitrogen, or both (Eklund *et al.* 2010). Synthesis of MXenes for biosensing, environmental, and other applications has been accomplished using various methods that affect the morphology, surface chemistry, etc.

Hydrofluoric acid (HF) etching is the most popular method for producing MXenes. For example, MAX phase Ti_3AlC_2 may be treated with a highly concentrated HF solution, during which time the aluminum is removed, resulting in the formation of layered MXene $Ti_3C_2T_x$. Upon removal of the aluminum, functional groups (-OH, -O, -F) are introduced to the surface of MXenes (Yazdanparast and Soltanmohammad, 2020). Adding these functional groups induces changes in MXenes' hydrophilicity, conductivity, and electrochemical properties. HF etching has uniformly proven to be a highly reliable and effective method of synthesizing high-quality MXenes, exhibiting both electrical conductivity and layered morphology (Benchakar *et al.* 2020).

2.2.1 Hydrofluoric Acid Etching of MAX Phases

The nature of hydrofluoric acid (HF) makes it very toxic and highly corrosive, which prevents large-scale and environmentally friendly production of MXenes due to the potential dangers and health risks associated with exposure to HF, both to humans and the environment, as well as the associated environmental costs. To solve this problem, researchers have been investigating a minimally intensive layer delamination (MILD) method that uses HF produced in situ for safely and controllably etching MAX phases. In the MILD method, fluoride salts (for example, lithium fluoride (LiF)) are mixed with hydrochloric acid (HCl) to generate HF in situ, which allows for the etching of MAX phases in a much safer and more controlled manner. MILD also improves MXene quality due to the production of larger flakes with fewer structural defects and greater stability than that found when using traditional etching processes (Eklund *et al.* 2010).

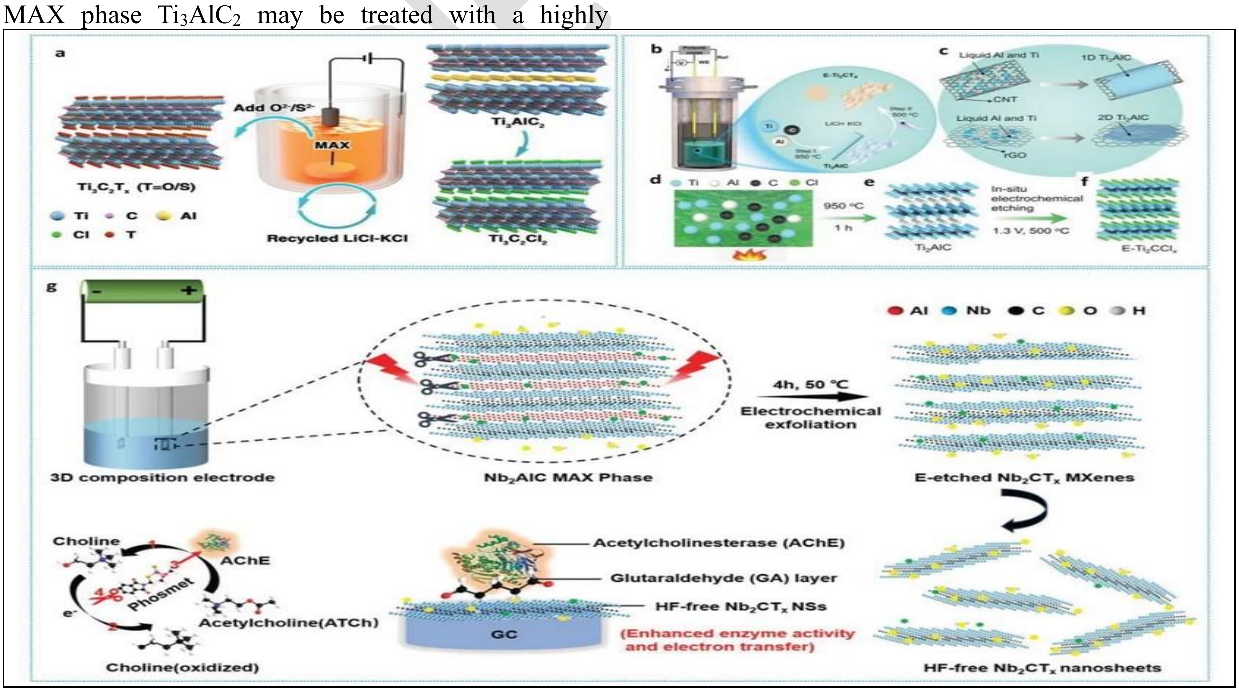

Fig. 4: Schematic illustration of sustainable MXene synthesis routes using HF-free etching and electrochemical methods. These approaches minimize hazardous chemicals while enabling controlled etching, improved safety, and environmentally benign production of high-quality MXenes with desirable structural and surface properties

A second important approach to producing MXenes is through the use of a molten salt etching method, which can provide an alternative to traditional salt etching processes that use fluoride salts as etching agents. In molten salt etching, MXene precursors (MAX phases) are treated using molten salts that are Lewis acids in nature (e.g., zinc chloride ($ZnCl_2$), copper chloride ($CuCl_2$)) at elevated temperatures. These salts can selectively remove the A-layer of MAX phases, producing MXenes that have modified surface chemistry and reduced fluoride terminations. The molten salt synthesis process offers the advantage of a minimal number of fluoride-related defects and lower environmental impacts, making it a viable option for future large-scale production of MXenes (Vaia *et al.* 2021).

The electrochemical etching technique has become increasingly popular recently as an environmentally friendly way of producing MXenes. Using this approach, MAX phases act as electrodes in an electrochemical cell where there is anodic etching (removing the A layer from the MAX phase) under controlled conditions, resulting in a mildly etched appearance. Additionally, with this method, there is greater control over the etching process (both in terms of duration and the amount of chemical required), therefore maintaining the structural integrity of MXene nanosheets. Furthermore, there appear to be fewer chemical hazards compared to other methods of producing MXenes and therefore more sustainable ways of producing MXenes for use in possible environmental applications (Peng *et al.* 2018).

2.2.2 Different MXene Synthesis Strategies

In recent years, chemical vapour deposition (CVD) has been identified as a new technique for creating ultrathin lamellar MXene films with precise control over their thickness and crystallinity (Wei *et al.* 2021). While traditional top-down etching techniques typically involve separating MXenes through the use of a strong acid to create the two-dimensional sheet (MXene) material, CVD utilises a more controlled, bottom-up approach by allowing the reactant gases to react with one another to form highly crystalline MXene structures. Additionally, CVD-manufactured MXenes tend to have better uniformity, conductivity, and stability than their counterparts produced via top-down methods (e.g., etching), making them superior options for high-performance sensors and electronic devices. However, the high cost and complexity associated with CVD prohibit large-scale production at this time (Zamhuri *et al.* 2021).

Once MXenes have been synthesised, post-synthesis delamination/exfoliation procedures are crucial to producing MXene nanosheets that are evenly dispersed and have good surface access to the surroundings being monitored (e.g., in sensing devices). Intercalation agents including dimethyl sulfoxide (DMSO), tetramethylammonium hydroxide (TMAOH), or organic molecules can all be used to increase the distance between the MXene layers so as to provide a mechanism through which MXenes can be decomposed to produce either few-layer or single-layer MXene nanosheets through exfoliation (Kobayashi *et al.* 2020). The exfoliation of MXenes results in XL (exfoliated nanosheet) MXenes having an increased amount of surface area and higher levels of electrical conductivity compared to other forms of MXenes (e.g., unexfoliated MXenes), making these forms of MXenes significantly more sensitive to targeted analytes and ultimately more actively promote binding events between biomolecules (i.e., higher probability of forming biointerruptive complexes) (Feng *et al.* 2021).

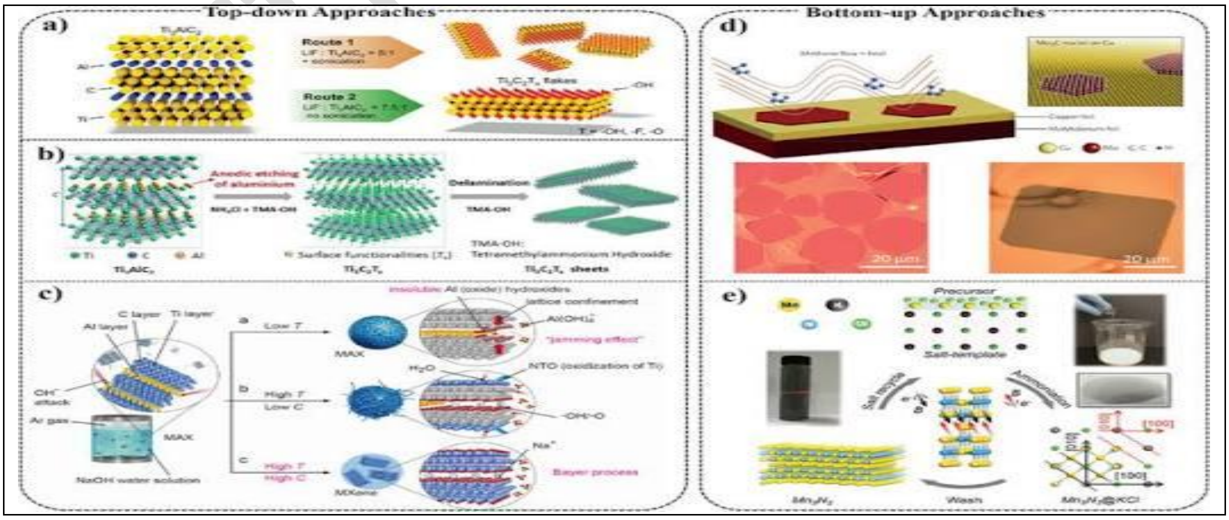

Fig. 5: Schematic representation of major MXene fabrication methods, including conventional HF etching, fluoride-free etching, molten salt synthesis, and chemical vapor deposition (CVD), these approaches differ in etching mechanism, environmental impact, synthesis conditions, and control over the structural and surface properties of MXenes

MXenes must be surface functionalized as a major aspect of their synthesis, and this will have a large effect on their electrochemical properties, level of hydrophilicity and degree of biocompatibility depending upon the specific surface termination chemistry. The surface functionalization of MXenes includes modifying the surfaces with nanoparticles, polymers, biomolecules, or heterostructures in order to improve both their stability and sensing performance. Surface functionalization also can be utilized to minimize their susceptibility to oxidation and increase their selectivity for target environmental pollutants (Sun *et al.* 2017).

MXenes have made great strides toward synthesis; however, many challenges still exist. The most significant challenge facing the synthesis, storage and use of MXenes is their high oxidation instability under ambient conditions, which can cause degradation of either conductivity or structural integrity. Additionally, it is difficult to consistently control flake size, layer thickness, defect density, and surface termination during the synthesis process. Developing scalable, cost-effective, environmentally friendly, and reproducible synthesis processes is, therefore, critical for the commercialization of MXene-based biosensors and environmental sensing platforms (Giménez *et al.* 2022).

Synthesis methods are an important method for determining the structural, electronic, and sensing properties of MXenes. The breakthroughs in etching, exfoliation, delamination and functionalization have led to the production of high-quality MXenes with adjustable physicochemical properties used in environmental monitoring applications. Continued work on safer and more sustainable synthesis methods should provide an accelerated path for developing MXene-based nanobiosensors for next-generation environmental sensing technologies (Lipatov *et al.* 2018).

Table 3 Critical comparison of MXene synthesis methods

Synthesis Method	Advantages	Limitations	Cost	Reproducibility	Defect Control	Environmental Impact
HF Etching	High yield, well-established, widely used	Hazardous HF, oxidation risk, safety concerns	Moderate	High	Moderate	Poor
MILD Etching (LiF + HCl)	Safer than HF, fewer defects, improved surface terminations	Longer processing time	Moderate	High	Good	Moderate
Molten Salt Etching	Fluorine-free synthesis, environmentally friendly	High temperature, complex equipment	High	Moderate	Excellent	Good
Electrochemical Etching	Green process, controllable etching, reduced chemical waste	Low production yield, difficult scale-up	Moderate	Good	Excellent	Excellent
Chemical Vapor Deposition (CVD)	High crystallinity, precise thickness control	Very expensive, sophisticated instrumentation	Very High	Excellent	Excellent	Moderate

Hydrofluoric acid (HF) etching has remained the most common technique for the synthesis of MXenes due to its effectiveness in providing high yields, yet it raises the issue of toxicity and environmental harm. The MILD process involves the use of fewer non-hazardous chemicals and offers better structural properties of MXenes with increased surface functionalization, which makes it perfect for biosensing purposes. Other methods such as molten salt and electrochemical etching also help with the environmental issues by minimizing the use of fluorinated compounds while allowing for a higher regulation of imperfections, although the desirability of these changes is limited by the issues of high production temperatures, process efficiency, and scalability. CVD allows obtaining high-quality crystalline MXene films with excellent consistency, although the need for advanced equipment and high operating costs significantly complicate the process of commercialization. Future work should focus on implementation of environmentally friendly, low-cost and scalable approaches for MXene synthesis, which would ensure high repeatability of produced MXenes with controlled properties.

2.3 Surface Functionalization and Biocompatibility

Because of the surface chemistry and terminal functional groups in MXenes (which include groups such as –OH, –O, and –F), different forms of surface modifications and binding of recognition platforms can be achieved. Thanks to these functional groups, nanoparticles, synthetic polymers, biopolymers, and other types of nanostructures can be added, which enables altering the MXene surface according to the needs of the given sensor application (Naguib *et al.* 2016).

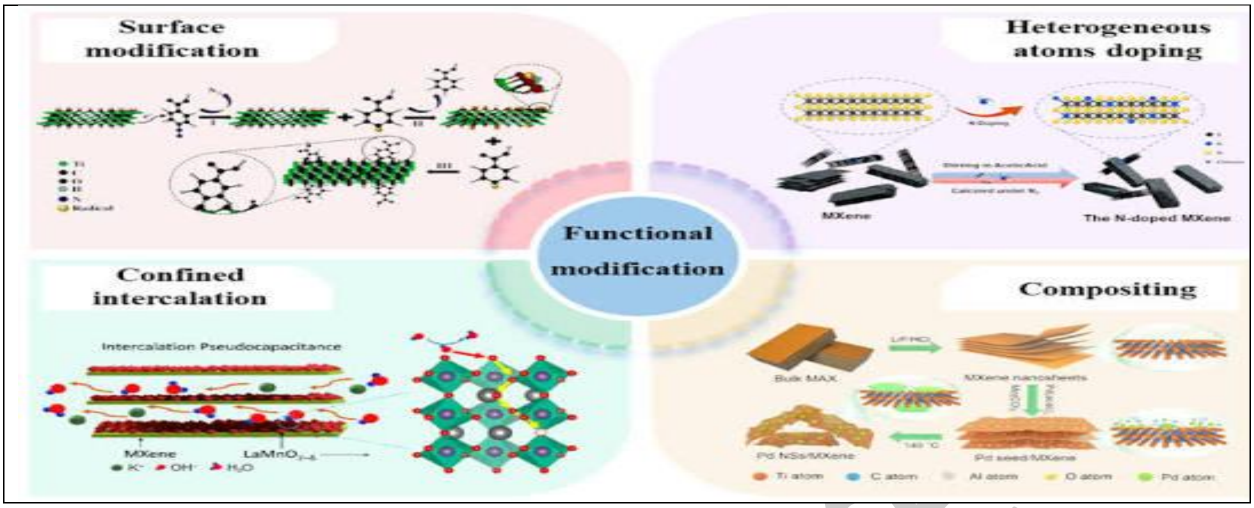

Fig. 6: Schematic representation of the major structural families of MXenes, including conventional, ordered double-transition-metal, vacancy-ordered (i-MXenes), and solid-solution MXenes. The figure highlights variations in atomic arrangement, composition, and surface termination groups (T_x), which contribute to the tunable physicochemical properties and broad application potential of MXene materials

Surface modifiers can be used to achieve surface functionalization, which may be realized through the use of covalent interactions with the target substrate, charge interactions, hydrogen bonding, or creating hybrid nanocomposite substances. Depending on their own tasks, such as improving analyte selectivity, increasing oxidation resistance, achieving biocompatibility and interface compatibility with biological recognition elements, the various processes are realized accordingly. Thanks to the increased surface engineering, various substances, such as different types of enzymes, antibodies or microbial cells, may be successfully fixed on one surface of the material (Sheng *et al.* 2019).

The combination of metallic nanoparticles and MXenes has altered the construction of hybrid sensing interfaces, as well as the possibility of using conductive polymers including PANI, PPy, PEG, or chitosan. Among these substances, chitosan is particularly appealing due to its ability to form films and its biodegradable and biocompatible properties (Taloub *et al.* 2019). Polymeric MXene hybrids can ensure better mechanical properties and stability in oxidation, and at the same time allow for the loading of biomolecules and the creation of proper interfaces for enzyme immobilization (Shi *et al.* 2019).

Carbon-based nanomaterials, such as graphene, graphene oxide, reduced graphene oxide, carbon nanotubes, and carbon quantum dots have also been combined with MXenes for making multifunctional sensing devices. Such hybrid combinations can enhance mechanical strength and stability in environmental conditions; however, the complexity of the manufacturing process can lead to inconsistencies in sensor performance (Nielsen, 1967).

The immobilization of biomolecules is a crucial technique to achieve specific recognition of a target. The use of enzymes, antibodies, aptamers, and DNA molecules enables MXenes to identify environmental pollutants selectively. MXenes modified with enzymes are used for detecting pesticides, heavy metals, and phenolic substances, whereas those modified with aptamers can differentiate between pathogens, toxins, and pharmaceuticals in the environment (Nhiem, 2026).

2.4 Principle of Biosensing Mechanisms

Nanobiosensors made of MXene integrate selective identification of contamination in the environment with a detectable signal output. The main function of MXene is to act as a sensing platform that enables interactions between identification materials and the target and allows for successful signal generation. Depending on the sensor design, this detection process can be transformed into an electrical, optical, or mechanical signal (Urbankowski *et al.* 2017). Therefore, the detection process involves three functional elements: target detection, MXene-based interaction, and signal output (Choudalakis and Gotsis, 2009).

The main factor that defines the selectivity of the sensor is the detection material, which may consist of enzymes, antibodies, aptamers, nucleic acids, microbial cells, and receptors (Carey et al., 2019). These agents are chosen according to the specific compound being detected and can be immobilized on the properly functionalized surface of MXene materials. The way the recognition process takes place is to keep the detection agent close to the MXene material while keeping its targeting feature (Liu *et al.* 2020; Zhao *et al.* 2020)

Numerous MXenes have been utilized in nanobiosensors, with electrochemical biosensing being the most common sensor type. This form of sensor can convert a biochemical reaction into an electrical signal (current/volt/impedance/conductivity) and is classified according to electrochemical measurement methodology as either amperometric, potentiometric, conductometric or impedimetric (Mehdi *et al.* 2021). MXenes offer an increased rate and efficiency of electron transfer than other materials, which makes them an ideal candidate for electrochemical biosensors, as their incorporation results in enhanced signal amplification and reduced detection limits of environmental contaminants (Lalegani *et al.* 2023).

A number of transduction methods are being studied, and the use of MXene sensors in conjunction with electrochemical techniques has been extensively researched. In this regard, MXenes can be applied at the sensing interface, and various means can be utilized for deriving the required analytical outcomes depending on the measurement employed. In particular, the analytical information can be obtained based on the changes in current, voltage, conductance and impedance. The use of MXenes in the measurements allows the transfer of charge and the amplification of the signal at the same time (Shah *et al.* 2008).

The amperometric systems provide analytical data related to the current resulting from oxidation/reduction of electroactive compounds. In general, MXene-coated electrodes have been employed to enhance the electrochemical response of systems that detect the presence of different contaminants like heavy metals, pesticides and phenolic compounds. In contrast, the potentiometric sensors work by measuring voltage changes at the interface where the target interacts with the selective membrane. The influence of MXenes on the performance of potentiometric sensors has been established. Finally, the impedimetric sensors rely on measuring the changes in charge transfer resistance and capacitance for obtaining relevant analytical information (Kumbhakar *et al.* 2021).

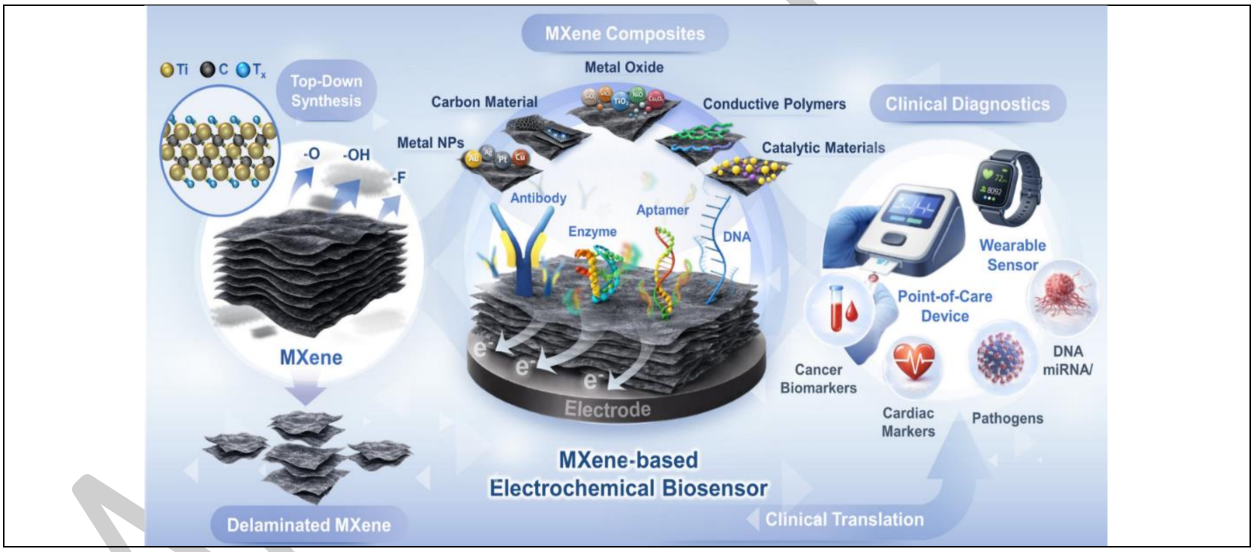

Fig. 7: Schematic illustration of MXene-based sensing platforms categorized into electronic, optical, and electrochemical sensors. The figure highlights the sensing mechanisms, signal transduction pathways, and the role of MXenes in enhancing sensitivity, selectivity, conductivity, and rapid detection for environmental and biomedical monitoring applications

Optical transduction represents another significant means of MXene-based biosensing. Optical systems can monitor all sorts of modifications in fluorescence, absorbance, luminous emissions, refractive index, or Raman scattering when the interaction with target substances occurs (Siwal *et al.* 2022). MXenes can be used in optical devices either in their pure form or in combination with other materials to constitute hybrid nanomaterials, utilizing some surface-enhanced Raman scattering technology, or similar (Cai *et al.* 2018). Fluorescence systems work based on measuring the variations in fluorescence intensity that appear due to the interaction of the fluorescent probe with MXenes. Such systems can be used to detect pesticides, toxins, and pathogens (Oshima, 2014). Colorimetric detection is rather straightforward as it relies on target-caused chemical/catalytic reactions, leading to colour modifications. This type of method has the great advantage of allowing simple visual or less advanced detection, which is valuable in environmental surveys. MXenes as well as MXene-containing hybrids have been studied in this regard (Ranjan *et al.* 2019; Natu and Barsoum, 2024).

Colorimetric detection systems enable analyte analysis with colour change by monitoring colour changes that occur due to both catalytically – and chemically-induced colour changes. The MXene material is particularly appealing for colourimetric environmental monitoring applications as its colour shifts can easily be observed with the naked eye (i.e. without underlying industrial instrumentation) while still having a rapid response time for environmental monitoring. The significant enhancement of the catalytic activity of MXene materials and their hybrid nanocomposite materials contributes greatly to increased sensing efficiency (overall) compared to the standard colourimetric sensing platform.

Field-effect transistors (FETs) rely on variations in the electrical properties of the sensor interface in response to the binding of the analyte for electronic sensing. MXene-based FETs utilize variations in the charge environment at the interface for detection (Ahmaruzzaman et *al.* 2013). Such systems have been developed for the analysis of metals, pathogens, and biomolecules, but challenges concerning device design and surface modification still exist for practical use (Anju *et al*. 2021). Another approach for detection is through the use of piezoelectric and acoustic wave principles, which exploit changes in weight or surface loading in analyte capture. QCM and SAW provide systems that convert the changes made at the surface into signals that could be measured (Thakur *et al.* 2026). MXenes can increase the performance of these systems; however, they are not extensively studied compared to electrochemical and optical methods (Vogel and Robinson, 2015).

Table 4 Surface Modifiers and Their Effects on MXene-Based Environmental Sensors

Surface Modifier	Primary Function	Effect on Sensor Performance	Advantages	Limitations	Typical Environmental Applications
Gold nanoparticles (AuNPs)	Improve electron transfer and biomolecule immobilization	Significantly increases sensitivity and lowers LOD	Excellent biocompatibility, high conductivity	High material cost	Heavy metal ions, pesticides, DNA biosensors
Silver nanoparticles (AgNPs)	Signal amplification	Improves sensitivity and antimicrobial activity	High catalytic activity	Oxidation and lower long-term stability	Water quality monitoring, pathogen detection
Platinum nanoparticles (PtNPs)	Electrocatalytic enhancement	Faster electron transfer and wider linear detection range	Excellent catalytic activity	Expensive	Electrochemical pollutant sensing
Carbon nanotubes (CNTs)	Increase conductivity and surface area	Improve response time and signal intensity	High mechanical strength	Agglomeration may occur	Heavy metal and pesticide sensing
Graphene	Improves conductivity and charge transport	Enhances sensitivity and stability	Large surface area	Requires additional functionalization	Electrochemical and optical biosensors
Conductive polymers (PANI, PEDOT, PPy)	Improve flexibility and biomolecule attachment	Better stability and repeatability	Easy fabrication	Moderate conductivity	Flexible and wearable biosensors
Biomolecules (Enzymes, Aptamers, Antibodies)	Specific target recognition	Improves selectivity and specificity	High recognition capability	Limited operational stability	Pathogens, toxins, pesticides

Surface functionalization is of great importance for the improvement of analytical performance of MXene based biosensors via electron transfer, active site density, and capacities for effective biomolecular immobilization. Metal nanoparticles such as AuNPs and PtNPs are known to improve sensitivity due to high electrical conductivity and catalytic activity; however, it may limit large scale implementation due to the material high cost. Carbon-based modifiers like graphene and carbon nanotubes enhance charge transport and mechanical stability, yet they must be optimized for avoiding agglomeration. Conductive polymers exhibit very good film-forming ability and improve stability in operation, being recommended for flexible sensing applications. Functionialization by biomolecules like enzymes, aptamers, and antibodies grants great selectivity to particular analytes, however biocomponents are characterized by low long-term operational stability under extreme environmental conditions.

Table 5 Biocompatibility, Toxicity, and Strategies for Improving the Biological Safety of MXene-Based Biosensors

MXene System	Biocompatibility	Reported Toxicity	Major Factors Affecting Toxicity	Strategies to Improve Biocompatibility	Representative Applications
$Ti_3C_2T_x$	Generally good at low concentrations	Oxidative stress at high concentrations	Concentration, oxidation state, exposure time	PEGylation, polymer coating, antioxidant modification	Electrochemical and wearable biosensors
Nb_2CT_x	Good	Limited toxicity reports	Surface chemistry, particle size	Surface functionalization	Electrochemical biosensors
V_2CT_x	Moderate	Requires further investigation	Metal ion release, concentration	Polymer encapsulation	Catalytic sensing
Mo_2CT_x	Promising	Limited biological studies available	Surface oxidation, dose	Composite formation	Optical and electrochemical biosensors

Despite the outstanding biocompatibility of MXenes for biosensing purposes, toxicity varies considerably between different MXenes and depends on the composition of the material, types and amounts of surface functional groups, particle size, concentration, oxidation state of the particles, and also on the duration of exposure. One of the main representatives of MXenes is $Ti_3C_2T_x$, which accounts for a large majority of all studies on MXenes, and has been shown to have low cytotoxicity at proper concentration. However, when subjected to any oxidation processes or prolonged exposure, MXenes can emit reactive oxygen species (ROS), cause oxidative stress and reduce cell viability. Moreover, surface oxidation might influence electrical conductivity and negatively affect the lifetime of the biosensor. It was shown in numerous studies that surface modification of MXenes by using polymers (e.g., polyethylene glycol, chitosan), antioxidants, as well as biocompatible nanocomposites might aid in reducing the toxicity of MXenes and achieving good colloidal stability of the sensor. However, despite these findings, long-term studies on the toxicity of MXenes and environmental risk assessment have not been conducted.

MXene-based biosensors use distinctive physicochemical features of two-dimensional transition metal carbides and nitrides for signal transmission. They possess metallic conductivity which allows electron transmission to occur rapidly. The surfaces of MXenes are terminated with groups (-OH, -O, and -F) that ensure complete binding of the biorecognition elements (enzymes, antibodies, aptamers, nucleic acids). The high specific surface area of MXenes means the availability of a number of active sites for binding recognized chemicals, resulting in high sensitivity, lower detection limits and efficiency of operation.

Recent studies are focusing more on the use of MXene-based biosensors in environmental samples as compared to laboratory-based solutions. Applications include numerous pollutants such as Pb^{2+}, Hg^{2+}, Cd^{2+}, pesticides, antibiotics, etc. present in natural waterways, groundwater, wastewater, agricultural runoff, and industrial wastewater. There are reports of good recovery; however, the functioning of the sensors may be hindered by matrix interference, including organic matter, ions, occult particles, and biofouling. As a result, upcoming studies should focus on long-term validation in the field, standard recovery studies, and comparisons with established techniques like ICP-MS, GC-MS, and HPLC.

Table 6 Comparison of MXene-Based Biosensor Types for Environmental Monitoring

Biosensor Type	Signal Transduction	Major Advantages	Limitations	Typical Environmental Targets
Electrochemical	Current, voltage, impedance	Highest sensitivity, ultra-low LOD, rapid response, portable	Electrode fouling, oxidation	Heavy metals, pesticides, antibiotics
Optical	SPR, SERS, absorbance	High selectivity, label-free detection	Expensive instrumentation	Pathogens, pharmaceuticals, pollutants
Fluorescence	Fluorescence quenching/FRET	Very low detection limits, multiplex detection	Photobleaching, fluorescent labeling	Toxins, pathogens, pesticides
Colorimetric	Visible color change	Simple, inexpensive, naked-eye detection	Lower sensitivity than electrochemical methods	Heavy metals, pesticides, water contaminants
Field-Effect Transistor (FET)	Conductivity modulation	Real-time monitoring, ultra-fast response, miniaturization	Fabrication complexity	Biomolecules, pathogens, metal ions
Piezoelectric (QCM/SAW)	Mass/frequency change	Label-free detection, high specificity	Sensitive to environmental vibration	Microorganisms, toxins, proteins

2.5 Classification of MXene-based Nanobiosensors

Nanobiosensors that are made from MXene can be categorized into several groups based on their principle of signal transduction. The main methods of MXene-based nanobiosensors include electrochemical, optical, fluorescent, colorimetric, field-effect transistor (FET), piezoelectric and acoustic wave. The performance of these techniques depends on the type of MXene used, its surface functionalization, the element used for recognition, the type of transducer, and the environment. Hence, comparing these devices requires a consideration of not only detection limits, but also selectivity, speed, stability, portability, complexity of construction, and other very real conditions.

2.5.1 Electrochemical biosensors

Electrochemical methodologies are one of the major types of research involving MXene based systems (Chaudhary *et al.* 2022). In these approaches, MXenes are included in electrodes with other sensing materials (enzymes, antibodies, aptamers, nucleic acids) (Downes *et al.* 2024; Sarycheva *et al*. 2022). Depending on the type of sensor deployed, various means can be used for the recognition of the target (current, potential, conductivity, or impedance changes) (Zhang *et al*. 2022). It has been shown that electrochemical devices using MXenes can be quite effective sensing heavy metals, pesticides, antibiotics, harmful microorganisms, and phenolic compounds in environmental samples. Their analytical features are attributed to the effective interfacial charge transfer and accessible interface that allows for sensing (Yankowitz *et al.* 2014). However, great analytical sensitivity does not necessarily guarantee high usability in practice. Electrode contamination, MXenes' oxidation, the interference of the surrounding media, and inconsistency in the making of the electrodes could affect reproducibility of results and long-term reliability. Thus, further research must demonstrate performance in real-world environment and show assessment results as well as stability and recovery measures instead of focusing on the results obtained in buffer solutions experiments.

2.5.2 Optical Biosensors

Using biosensors based on optical MXene enables the monitoring of target-related variations in optical signals (Stajic, 2017). In this regard, MXenes can be used in different ways for the construction of optical sensing devices through either direct use of MXenes or their hybridization with other kinds of nanomaterials. For this purpose, their combination with noble metal-based nanoparticles has been analyzed to facilitate the generation of optical signals and interfacial interactions (Hassan *et al.* 2018). Such constructions can be applied to identify pesticides, toxins, heavy metals, drugs, and pathogens from environmental samples (Ji *et al.* 2021). In addition, MXene-based hybrid nanocomposite allows enhancing the interaction between target analytes and sensing interface and thus improving the quality of analysis (Kurra and Gogotsi, 2019). However, it should be noted that optical systems may demand more sophisticated equipment than electrochemical or colorimetric systems.

2.5.3 Fluorescence Biosensors

Fluorescence systems rely on the principle of altered emission of fluorescent probes upon interaction with the target analyte for effective detection (Li *et al.* 2019). MXenes can be part of fluorescence sensing interfaces where target detection may induce either fluorescence quenching or fluorescence recovery (Jin and Bai, 2022). Fluorescent probes are bound or anchored to the MXene surface to allow alterations caused by the target analyte to be measurable in terms of fluorescence (Ullah *et al.* 2024). Fluorescence resonance energy transfer (FRET) is one of the MXene-based fluorescent mechanisms, in which interactions between fluorescent donors and MXene acceptors influence the emission signals (Zheng *et al.* 2021). These systems have been studied for use in detecting pesticides, drugs, toxins, and bacteria, which results in very low detection limits and high selectivity (Zamhuri *et al.* 2021). However, issues such as fluorescent labeling, stability of probes, photobleaching, and the need for controlled optical measurement conditions prevent their use in field applications Therefore, validation in complex real-life samples and development of convenient portable readout systems must be done to make them viable.

2.5.4 Colorimetric Biosensors

Fluorescence biosensors are analytical tools that detect target analytes by measuring changes Colorimetric biosensors use simple mechanisms where the presence of target analytes causes a color change that is detectable either visually or with a simple optical instrument. In MXene-based systems, color development can occur due to either a chemical or a catalytic process at the sensing interface (Sivasanjarapillai *et al.* 2022). MXenes modified with specific functional groups and hybrids based on MXenes can be used in catalytic or interfacial processes that underlie the produced color change (Kang *et al.* 2022). The main feature leading to the advantages of colorimetric systems is their simplicity together with the possibility of inexpensive, instrument-free environmental testing. They have been studied and used for analyzing pollutants such as pesticides, toxins, and water quality parameters (Griffith *et al.* 2020). However, colorimetric sensors tend to be less sensitive than electrochemical or fluorescence systems and can be affected by the color and turbidity of the tested samples. Their primary area of applicability seems to be the quick preliminary experiments rather than substitution of the modern lab methods with high sensitivity.

2.5.5 FET-based Biosensors

FET type biosensors work by detecting the changes in the electrical properties of the sensing channel when it interacts with the analyte (Ying *et al.* 2015). The system has a recognition element on the sensing interface and when the target binds to it, it changes the electrical environment which modifies the response being measured (Harris *et al.* 2015). MXenes are excellent at what they do thanks to their adjustable surface chemistry and their electrical properties which makes them a great fit for FET sensing systems (Rajapakse *et al.* 2021). MXene-based FET systems have been used in the detection of different substances like heavy metals, toxins, and biological materials and have shown promising results (Ren *et al.* 2015). There are many advantages of using MXenes in FETs such as speed as well as miniaturization of the systems (Ding *et al.* 2023). Yet, problems such as manufacturing processes, surface modifications and their effects on other variables must be addressed in order to successfully implement them in practice.

Table 7 Key Challenges, Commercialization Barriers, and Possible Solutions for MXene-Based Environmental Biosensors

Challenge	Current Status	Impact on Commercialization	Possible Solution
HF-based synthesis	Hazardous	Poor industrial scalability	Green etching/MILD
Oxidation	Severe	Reduced shelf life	Polymer coating, antioxidants
Batch variability	High	Poor reproducibility	Standardized synthesis protocols
High production cost	High	Limits commercialization	Continuous manufacturing
Device packaging	Limited	Low durability	Flexible encapsulation
Regulatory approval	Not established	Delayed market entry	Toxicity and environmental validation

While MXene offers exciting performances in laboratory conditions, completely new and additional issues pop up when it comes to commercializing MXene-based environmental biosensors, such as the production process, stability, reproducibility, device integration, etc (Iravani and Varma, 2022). Most of the methods of MXene production are associated with toxic reagents and different stages of production which complicates the process of commercialization and increases its cost (Lee *et al.* 2017). Furthermore, the differences in precursors, etching process, surface terminations, and other post-processing techniques lead to uneven performance (Gulzar *et al.* 2024; An *et al.* 2024).

The issue of oxidation poses a significant challenge to $Ti_3C_2T_x$, as it can lead to deterioration of the sensor, which would affect its ability to sense at the storage and operational stages. The large-scale use of $Ti_3C_2T_x$ will require improvements in production methods, the use of protective coats and packaging, and establishment of efficient integration of MXenes in portable and flexible devices (Choudalakis and Gotsis, 2009). In addition to this, there is a need for standardized production methods, quality control of manufacturing, regulatory approvals, and validation with real environmental samples for lab-scale applications to be translated to larger production and use of $Ti_3C_2T_x$ and other MXenes. This implies that the future work should be based on scalable synthesis of oxydation resistant MXenes and repeatable production of devices for practical use (Wassei and Kaner, 2010).

3. DISCUSSION

MXene-based nanobiosensors hold significant promise in the field of detection of environmental pollutants. However, while studies claims of their analytical merits, it is imperative to understand that there is variation in the materials used and different operating conditions. MXenes in electrochemical, optical, fluorescent, and similar detection configurations have also been linked to improved sensitivity, faster detection, and low detection limits of contaminants such as heavy metals, pesticides, antibiotics, endocrine disruptors, organic contaminants, and various microorganisms (Kaul, 2014; Raghvendra, 2018). However, the progress should not be construed as a result of the properties of MXenes alone. The success of a sensor depends on the nature of MXenes employed, their method of preparation, type of surface modification, functionalization, type of transducer, methods of signal generation, etc. As a consequence, difficulties arise in interpreting the performance since the same machines are seldom used for measuring the concentration of a particular substance (Akhter *et al.* 2023).

A thorough comparison of the aforementioned platforms shows that improving one of the analytical aspects does not increase the sensor performance as a whole. MXene electrosensors have a small limit of detection and high response time, while the optical or fluorescence-based sensors demonstrate the possibility of achieving some different advantages in relation to signal generation and multiplex analysis. However, it is impossible to declare that one of the sensing technologies is better than others, as it depends on both the analyte and sensor design. Also, although modification of the sensor surface using enzymes, antibodies, aptamers, or molecularly imprinted polymers enhances the recognizability of analytes, additional functional layers require additional processes of fabrication and influence the sensor accessibility. That is why the choice of the sensing technique is determined by the application need rather than the goal of maximum analytical sensitivity (Catania *et al.* 2021).

Hybridization provides an additional instance of trade-offs that occur in the design of MXene sensors. Various elements, such as metal nanoparticles, metal-organic frameworks, carbon nanotubes, graphene derivatives, conducting polymers, and quantum dots are also known to heighten the sensory responses due to their impact on interfacial interactions. Nevertheless, although some methods of classic analytical techniques exhibit better analytical performance, it is important to consider the additional complexity of hybrid structures. For instance, while hybrid structure can have the lowest detection limit, the complexity of the production and manufacturing increases. In some situations, hybrid structures may also affect the stability of the sensor. Therefore, hybridization is not always advantageous but consistent with the specific benefits justifying complexity of the technologies being used (Meitong *et al.* 2021).

Comparing MXenes with other two-dimensional materials reflects the fact that they can't be classified as the best materials. Graphene, for example, is a great material when it comes to mechanical and electrical performance; however, it usually has to be modified for efficient functionalization. MoS_2 has good catalytic properties, but its relatively low electric conductivity with respect to this material can hinder its efficiency in electrochemical use. Black phosphorus has great electronic characteristics but it is not stable enough compared to some other materials, and $g\text{-}C_3N_4$ is also good for photocatalysis but less conductive in comparison with MXenes. Therefore, the choice of two-dimensional material depends more on the needs of the application than on the general one. MXenes are fairly good materials from the viewpoint of electrical and surface-chemical characteristics, but their tendency to oxidation is a serious drawback that can negate all analytical advantages in a prolonged operation.

Oxidation is an important problem according to the literature among the issues identified because it connects the stability of the materials with the efficiency of the sensors. One of the most studied MXenes, $Ti_3C_2T_x$ can be oxidized when oxygen and humidity are present. This process leads to the formation of titanium oxides which decreases the electrochemical activities of the material (Mehranfar *et al.* 2022) This makes this process challenging in terms of applying the sensors for environmental monitoring since the conditions that make the monitoring possible, such as the presence of humid medium and oxygen, lead to a degradation of the materials. Many approaches were tried such as anti-oxidation layers, encapsulation with polymers, storing in neutral environment, and usage of oxides (Afshari *et al.* 2023). Nevertheless, these techniques should be treated as those that ensure the stabilization of the materials rather than full solutions to the problem. As an example, polymers may create some stability but can also bring some barriers to create an access to the sensing surface, while controlled storage can protect the material but does not guarantee that it will not be oxidized in real life.

One more relevant finding made on the MXenes incorporated sensors focuses on the laboratory/practical use difference. A lot of MXene base sensors demonstrate high analytical performance in a laboratory setting but, unfortunately, real samples contain organic matter, dissolved salts, microbial organisms and other interfering substances, along with the variable pH, temperature, and ionic strength of the system. All these factors change the transport of the analyte, create non-specific interactions, and cause biofouling. Thus, a low value under laboratory conditions does not mean it has to be the same in wastewater, surface water, soil extracts, or other complex matrices. Hence, the discrepancies in the sensitivity results of the sensors among different investigations may not be caused only by properties of the materials but also by some sample composition and experimental design aspects. Finally, it is clear that in order to prove the claims about the benefits of the methods under discussion the validation with the real sample has to take place.

Commercialization is similarly affected by the challenges mentioned before. While MXenes have shown good sensor properties, their commercialization faces difficulties due to problems with reproducibility and ease of large-scale production, complexity of synthesis, costs of production, variations between batches, few packaging options, and weak regulatory frameworks. Use of dangerous etching techniques as well as the issues with the material properties only make the scale-up more complicated. The problems indicate that the major challenge of commercialization is not just making sensors more sensitive but also allowing for getting sensors with reliable composition, surface chemistry, response, shelf life, and stability. Therefore, it is necessary to develop standard protocols and criteria. Moreover, green and non-fluorine synthesis methods have a potential for addressing some environmental problems, but their practicality in the industry should be estimated according to cost, yield, quality, and reproducibility of the manufactured product and not just according to their ecological benefits.

Environmental safety is yet another issue that needs resolution in the process of MXene-based sensor development. The existing studies show that long-term toxicity and environmental effects remain poorly understood. Importantly, toxicity cannot be generalized across all types of MXenes because different factors influence their environmental behavior, such as the composition of the material, the surface functional groups, the characteristics of the particles, the concentration of MXenes, exposure conditions, and degradation state. The oxidation of MXenes may also cause changes in the chemical composition of the materials during their lifespan, which means that it is necessary to study both the pristine MXenes and their degradation products during the assessments. Therefore, only short-term measurements of toxicity cannot guarantee environmental safety. Future evaluations should include long-time exposure, degradation, environmental fate, release from the sensor systems, and environmental impact. Life cycle assessment needs to include processes that occur from the production of raw materials and synthesis of MXenes till the production of devices, their usage, degradation, disposal, or recycling.

Incorporating artificial intelligence, machine learning, and Internet of Things technologies is seen as a potentially valuable step towards MXene-based environmental monitoring, though it is not currently backed by strict evidence supporting claims in this regard. While AI can help with automatic signal interpretation, detecting anomalies, monitoring remotely, or suggesting environmental predictions such performance relies on acquiring large and representative datasets properly labelled under real-life conditions. The reliability of ML models may also be influenced by the type of sensor fabrication, environmental matrices, sensor life cycle, and baseline drift. As a result, the proposed AI incorporation variable value rather than established value. In particular, the impact of AI on reducing false positive results needs validation through proper experiments with independent datasets and regarded under real environmental conditions. It is necessary to assess the benefits of AI-assisted signal processing in comparison to conventional techniques through applying relevant performance metrics.

The use of technologies such as artificial intelligence (AI), machine learning (ML), and Internet of Things (IoT) can be seen as a new trend for environmental monitoring with the help of MXenes. AI-enabled technologies might perform functions like detection of anomalies, classification of data from sensors and monitoring remotely in cases when a sufficient amount of data is (Pogorielov *et al*. 2021). Nevertheless, there is still not enough experimental support in the existing literature to prove that AI works specifically to reduce the number of false-positive findings in environmental biosensors that are based on MXenes. Various factors like sensor drift, heterogeneous nature of environmental matrices, differences between devices, small amounts of training data, and different experimental conditions can negatively affect the performance of AI systems. Thus, all claims on improved accuracy of detection and lower number of errors should not be considered valid yet. Future work should focus on the experiment with the use of the comparison between conventional approach and the approaches involving AI while using validated data obtained from the samples taken from real environment.

4. CONCLUSION

This review provides an overview of the recent developments in MXene-based nanobiosensors for the detection of environmental pollutants, focusing on their exceptional physicochemical characteristics, methods of preparation, surface modifications, and biosensing mechanisms along with environmental monitoring applications. Featuring combination of exceptional electrical conductivity, good hydrophilicity, tunable surface chemistry, high specific surface area and good biocompatibility, MXenes are becoming one of the most promising two-dimensional materials for the materials of the future. Latest researches indicate that MXene-sourced biosensors provide excellent analytic properties such as high sensitivity, excellent selectivity, high speed of response, and ultra-low limits of detection for heavy metals, pesticides, pharmaceutical residues, pathogens and other contaminants in water, soil and air environments. There have been major advancements in improving safer synthesis methods, such as dry layer delaminating, electrochemical etching, molten salt technique, and fluorine-free production technology,that make it possible to obtain better quality materials while causing no harm to the environment. Moreover, the process of surface engineering at the expense of polymers, noble metals nanoparticles, carbon nanomaterials, aptamers, enzymes, and antibodies significantly improves the oxidation resistance, biomolecule desorption, and electron transfer efficiency of MXenes. The development of such electrochemical, optical, fluorescence, colorimetric, and field-effect transistor-based sensing techniques has proved the effectiveness of MXenes for various environmental monitoring purposes.

In spite of the many advancements made in this field, it is worth noting the obstacles which hinder the successful implementation of MXene-based nanobiosensors in terms of their practical use. One of the most important issues affecting the stability of MXenes over time is their ability to oxidize at ambient conditions. Additionally, the different procedures employed for the synthesis may also lead to batch-to-batch variability of MXenes making it impossible to achieve a very high level of reproducibility. Moreover, manufacturing the products on a large scale is difficult due to the inherent complexity of the manufacturing processes, high production costs, and lack of the standardization of the processes. In addition, the research studies aimed at examining long-term negative effects of the environmental impact of MXenes and their toxicity are still at an early stage of development. In summary, this review provides a comprehensive and up-to-date overview of MXene-based nanobiosensors by combining the recent achievements in the field of material development, surface modification, sensing mechanisms, environmental applications, current shortcomings, and commercialization. Contrary to numerous previous reviews, which highlighted biosensor performance at large, this work addresses important issues hindering practical application of MXene-based technologies and proposes adequate measures for further progress.

FUTURE RESEARCH

Future studies should focus on the creation of oxidation-resistant MXenes through advanced surface passivation techniques and eco-friendly approaches that do not involve HF, and approaches for MXene production in compliance with the standards and economically feasible methods for their mass production. Furthermore, there is a need for researchers to emphasize the importance of testing MXene-based sensors in real-world conditions rather than only in laboratory conditions. The latest technological changes, including artificial intelligence and others, could enhance the functionalities of MXene-based environmental sensing platforms by making it possible to perform automated data processing, remote monitoring of the environment, and predictive analysis. The use of modern technologies is still in its early stages and requires a lot of experimental validation before being put into practice. MXene-based nanobiosensors need not just better materials and technology to produce them economically, but also standardized systems for their production and checking the quality of the produced technology. Moreover, it is necessary to provide thorough environmental safety assessment as well as evaluation of toxicity in the in a long-term way and be complied with environmental regulations.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Afshari, P., Maryna, P., Lira, C., Katnam, K. B., Mahdi, B. and Hamed, Y. N., Mechanical Strain Tailoring via Magnetic Field Assisted 3D Printing of Iron Particles Embedded Polymer Nanocomposites, *Macromol. Mater. Eng.*, 308(11), 2300194(2023). https://doi.org/10.1002/mame.202300194

Ahmaruzzaman, M., MXenes and MXene-supported nanocomposites: A novel materials for aqueous environmental remediation, *RSC Adv.*, **12**(53), 34766–34789 (2022). https://doi.org/10.1039/D2RA05530A

Akhter, R. and Maktedar, S.S., MXenes: A comprehensive review of synthesis, properties, and progress in supercapacitor applications, *J. Materiomics*, **9**(6), 1196–1241 (2023). https://doi.org/10.1016/j.jmat.2023.08.011

Ali, A., Majhi, S. M., Siddig, L. A., Deshmukh, A. H., Wen, H., Qamhieh, N. N., Greish, Y. E. and Mahmoud, S. T., Recent advancements in MXene-based biosensors for health and environmental applications—a review, *Biosens.*, 14(10), 497(2024a). https://doi.org/10.3390/bios14100497

Ali, M. R., Bacchu, M. S., Al-Mamun, M. R., Hossain, M. I., Khaleque, A., Khatun, A., Ridoy, D. D., Aly, M. A. S. and Khan, M. Z. H., Recent advanced in MXene research toward biosensor development, *Critical Rev. Anal. Chem.*, 54(6), 1381-1398(2024b). https://doi.org/10.1080/10408347.2022.2115286

An, T., Zhang, Y., Wen, J., Dong, Z., Du, Q., Liu, L., Wang, Y., Xing, G. and Zhao, X., Multi-level pyramidal microstructure-based pressure sensors with high sensitivity and wide linear range for healthcare monitoring, *ACS sensors*, 9(2), 726-735(2024). https://doi.org/10.1021/acssensors.3c02001

Anasori, B., Maria, L. R. and Yury, G., 2D metal carbides and nitrides (MXenes) for energy and environmental applications, *Nat. Rev. Mater.*, 2(2), 16098(2020). https://doi.org/10.1038/natrevmats.2016.98

Anju, S. and Mohanan, P. V., Biomedical applications of transition metal dichalcogenides (TMDCs), *Synth. Met.*, 271, 116610(2021). https://doi.org/10.1016/j.synthmet.2020.116610

Askari, S., Salimifard, H., Alavi, R., Eskandari, M., Zarepour, A., Khosravi, A., Iravani, S. and Zarrabi, A., Two-dimensional nanomaterial-based aptasensors: graphene and MXenes as emerging biosensing platforms, *ACS Appl. Nano Mater.*, 8(37), 17819-17862(2025). https://doi.org/10.1021/acsanm.5c03078

Ayodhya, D., A review of recent progress in 2D MXenes: Synthesis, properties, and applications, *Diam. Relat. Mater.*, 132, 109634(2023). https://doi.org/10.1016/j.diamond.2022.109634

Benchakar, M., Lola, L., Cyril, G., Bilyk, T., Moris, C., Canaff, C., Nadia, G., Sophie, M., Hanna P., Simon, H., Patrick, C., Pacaud, J., Vincent, M., Micheal, B. W., Habrioux, A. and Stephane, C., One MAX phase, different MXenes: A guideline to understand the crucial role of etching conditions on $Ti_3C_2T_x$ surface chemistry, *Appl. Surf. Sci.*, 530 147209(2020). https://doi.org/10.1016/j.apsusc.2020.147209

Cai, Z., Liu, B., Zou, X. and Cheng, H. M., Chemical Vapor Deposition Growth and Applications of Two-Dimensional Materials and Their Heterostructures, *Chem. Rev.*, 118(3), 6091-6133(2018). https://doi.org/10.1021/acs.chemrev.7b00536

Carey, M. S., Sokol, M., Palmese, G. R. and Michel, B. W., Water Transport and Thermomechanical Properties of Ti_3C_2Tz MXene Epoxy Nanocomposites, *ACS Appl. Mater. Interf.*, 11(42), 39143-39149(2019). https://doi.org/10.1021/acsami.9b11448

Catania, F., Elena, M., Mauro, G., Pravin, J., Luca, L., Alberto, T. and Bartoli, M., A review on recent advancements of graphene and graphene-related materials in biological applications, *Appl. Sci.*, 11(2), 614(2021). https://doi.org/10.3390/app11020614

Chaudhary, V., Neugebauer, P., Mounkachi, O., Lahbabi, S. and El Fatimy, A., Phosphorene—an emerging two-dimensional material: recent advances in synthesis, functionalization, and applications, *2D Mater.*, 9(3), 032001(2022). https://doi.org/10.1088/2053-1583/ac6dc2

Choudalakis, G. and Gotsis, A. D., Permeability of polymer/clay nanocomposites: A review, *Eur. Polym. J.*, 45(4), 967-984(2009). https://doi.org/10.1016/j.eurpolymj.2009.01.027

Deng, Q., Zhou, F., Ben, Q., Feng, Y. and Xu, Z., Eco-friendly poly(vinyl alcohol)/delaminated V2C MXene high-k nanocomposites with low dielectric loss enabled by moderate polarization and charge density at the interface, *Ceram. Int.*, 46(17), (2020). https://doi.org/10.1016/j.ceramint.2020.07.218

Ding, L., Wei, Y., Li, L., Zhang, T., Wang, H., Xue, J., Ding, L.X., Wang, S., Caro, J. and Gogotsi, Y., MXene molecular sieving membranes for highly efficient gas separation, *Nat. Commun.*, 9(1), 155(2018). https://doi.org/10.1038/s41467-017-02529-6

Downes, M., Shuck, C. E., McBride, B., Busa, J. and Gogotsi, Y., Comprehensive synthesis of $Ti_3C_2T_x$ from MAX phase to MXene, *Nat. protocols*, 19(6), 1807-1834(2024). https://doi.org/10.1038/s41596-024-00969-1

Eklund, P., Manfred, B., Jansson, U., Hans, H. and Lars, H., The M+1AX phases: Materials science and thin-film processing, Thin Solid Films, 518(8), 1851–1878(2010). https://doi.org/10.1016/j.tsf.2009.07.184

Eklund, P., Manfred, B., Ulf, J., Hans, H. and Lars, H., The M+1AX phases: Materials science and thin-film processing, *Thin Solid Films*, 518(8), 1851–1878 (2010). https://doi.org/10.1016/j.tsf.2009.07.184

Fan, F. R., Wang, R., Zhang, H. and Wu, W., Emerging beyond-graphene elemental 2D materials for energy and catalysis applications, *Chem. Soc. Rev.*, 50(19), 10983-11031(2021). https://doi.org/10.1039/c9cs00821g

Fan, Y., Li, L., Zhang, Y., Zhang, X., Geng, D. and Hu, W., Recent advances in growth of transition metal carbides and nitrides (MXenes) crystals, *Adv. Funct. Mater.*, 32(16), 2111357(2022). https://doi.org/10.1002/adfm.202111357

Feng, A., Hou, T., Jia, Z., Yi, Z., Fan, Z. and Wu, G., Preparation and characterization of epoxy resin filled with $Ti_3C_2T_x$ MXene nanosheets with excellent electric conductivity, *Nanomater.*, 10(1), 162 (2020a). https://doi.org/10.3390/nano10010162

Feng, Y., Hui, W., Xu, J., Du, X., Xu, C., Du, Z. and Wang, H., Fabrication of MXene/PEI functionalized sodium alginate aerogel and its excellent adsorption behavior for Cr(VI) and Congo Red from aqueous solution, *J. Hazard Mater.*, 416, 125777(2021). https://doi.org/10.1016/j.jhazmat.2021.125777

Feng, Y., Zhou, F., Bo, M., Huang, Y., Deng, Q. and Peng, C., Enabling high dielectric response in PVDF/V2C MXene-TiO_2 composites based on nontypical V-F-Ti bonding and fermi-level overlapping mechanisms, *J. Phy. Chem. C*, 124(50), 27780-27789(2020b). https://doi.org/10.1021/acs.jpcc.0c08444

Fuhrer, M. S., Lau, C. N. and Allan, M. H., Graphene: Materially Better Carbon, *MRS Bull.*, 35(4), 289–295(2010). https://doi.org/10.1557/mrs2010.551

Giménez, R., Berna, S., San, M. V. and Juan, C. C., Recent Advances in MXene/Epoxy Composites: Trends and Prospects, *Polym.*, 14(6), 1170(2022). https://doi.org/10.3390/polym14061170

Griffith, K. J., Hope, M. A., Philip, R. J., Anayee, M., Yury, G. and Grey, C. P., Bulk and Surface Chemistry of the Niobium MAX and MXene Phases from Multinuclear SolidState NMR Spectroscopy, *J. Am. Chem. Soc.*, 142(44), 18924-18935(2020). https://doi.org/10.1021/jacs.0c09044

Gulzar, A., Haleem, A., Rehman, T. U., Ullah, M., Shah, A. and Ullah, I., Harnessing the power of MXenes: a comprehensive exploration of their photocatalytic potential in mitigating hazardous dyes and CO_2 reduction, *Discover Mater.*, 4(1), 15(2024). https://doi.org/10.1007/s43939-024-00081-x

Guo, L., Zhang, Z., Li, M., Kang, R., Chen, Y., Song, G., Han, S. T., Lin, C. T., Nan, J. and Yu, J., Extremely high thermal conductivity of carbon fiber/epoxy with synergistic effect of MXenes by freeze-drying, *Compos. Commun.*, 19, 134-141(2020). https://doi.org/10.1016/j.coco.2020.03.009

Hajian, S., Dinesh, M., Binu, B. N. and Massood, A. Z., MXene-based flexible sensors: A review, *Front. Sens.*, 3, 11006749(2022). https://doi.org/10.3389/fsens.2022.1006749

Hao, S., Han, H., Yang, Z., Chen, M., Jiang, Y., Lu, G., Lun, D., en, H., Li, H., Liu, J., Wu, L., Wang, Z. and Wang, F., Recent Advancements on Photothermal

Conversion and Antibacterial Applications over MXenes-Based Materials, *Nano-Micro. Lett.*, 14(1), 178 (2022). https://doi.org/10.1007/s40820-022-00901-w

Harris, K. J., Bugnet, M., Micheal, N., Barsoum, M. W. and Gillian, G. R., Direct measurement of surface termination groups and their connectivity in the 2D MXene V2CTx using NMR spectroscopy, *J. Phy. Chem. C,* 119(24), 13713-13720(2015). https://doi.org/10.1021/acs.jpcc.5b03038

Hassan, A., Yvon, S. and Sawan, M., GaN Integration Technology, an Ideal Candidate for High-Temperature Applications: A Review, *IEEE Access*, 6, 78790–78802(2018). https://doi.org/10.1109/ACCESS.2018.2885285

Iravani, S. and Varma, R. S., MXene-based composites as nanozymes in biomedicine: a perspective, *Nano-Micro Lett.*, 14(1), 213(2022). https://doi.org/10.1007/s40820-022-00958-7

Ji, C., Cui, H., Mi, H. and Yang, S., Applications of 2d mxenes for electrochemical energy conversion and storage, *Energies (Basel*), 14(23), 8183(2021). https://doi.org/10.3390/en14238183

Jin, C. and Bai, Z., MXene-Based Textile Sensors for Wearable Applications, *ACS Sens.*, 7(4), 929-950(2022). https://doi.org/10.1021/acssensors.2c00097

Kang, H., Han, L., Chen, S., Xie, S., Li, M., Fang, Q. and He, S., Research Progress on TwoDimensional Layered MXene/Elastomer Nanocomposites, Polym., 14(19), 4094(2022). https://doi.org/10.3390/polym14194094

Kaul, A. B., Graphene and two-dimensional layered materials for device applications, *IEEE*, 1-4(2013). https://doi.org/10.1109/NANO.2013.6720961

Kaul, A. B., Two-dimensional layered materials: Structure, properties, and prospects for device applications, *J. Mater. Res.*, 29(3), 348–361(2014). https://doi.org/10.1557/jmr.2014.6

Khazaei, M., Arai, M., Sasaki, T., Ranjbar, A., Liang, Y. and Yunoki, S., OH terminated two-dimensional transition metal carbides and nitrides (MXenes) as ultralow work function materials, *Adv. Funct. Mater.*, 23, 2185-2192. https://doi.org/10.1103/PhysRevB.92.075411

Kobayashi, T., Sun, Y., Prenger, K., Jiang, D., Micheal, N. and Merek, P., Nature of Terminating Hydroxyl Groups and Intercalating Water in Ti3C2TxMXenes: A Study by 1H Solid-State NMR and DFT Calculations, *J. Phy. Chem. C.*, 124(25), 13649-13655 (2020). https://doi.org/10.1021/acs.jpcc.0c04744

Kumbhakar, P., Chowde, G. C. and Tiwary, C. S., Advance Optical Properties and Emerging Applications of 2D Materials, *Front Mater.,* 8, 721514(2021). https://doi.org/10.3389/fmats.2021.721514

Kurra, N. and Yury, G., MXenes: From Fundamental Science to Emerging Applications, *ECS Meeting Abstracts*, MA2019-01(12), 815 (2019). https://doi.org/10.1149/ma2019-01/12/815

Lalegani, D. M., Sales, R., Ali, Z., Hamed, Y. N. and Bodaghi, M., Soft pneumatic actuators with integrated resistive sensors enabled by multi-material 3D printing, *Int. J. Adv. Manuf. Technol*., 128(9-10), 4207-4221(2023). https://doi.org/10.1007/s00170-023-12181-8

Lee, E., VahidMohammadi, A., Prorok, B. C., Yoon, Y. S., Beidaghi, M. and Kim, D. J., Room temperature gas sensing of two-dimensional titanium carbide (MXene), *ACS Appl. Mater. Interf.*, 9(42), 37184-37190(2017). https://doi.org/10.1021/acsami.7b11055

Li, M., Lu, J., Luo, K., Li, Y., Keke, C., Ke, C., Jie, Z., Rosen, J., Lars, H., Per, E., Per, P. O., Du, S., Chai, Z., Huang, Z. and Huang, Q., Element replacement approach by reaction with Lewis acidic molten salts to synthesize nanolaminated materials and MXenes, *J. Am. Chem. Soc.*, 141(11), 4730–4737(2019). https://doi.org/10.1021/jacs.9b00574

Li, Z. Y., Li, D. Y., Huang, L., Hu, R., Yang, T. and Yang, Y. H., An electrochemical aptasensor based on intelligent walking DNA nanomachine with cascade signal amplification powered by nuclease for Mucin 1 assay, *Anal. Chimica Acta*, 1214, 339964(2022). https://doi.org/10.1016/j.aca.2022.339964

Lipatov, A., Lu, H., Mohamed, A., Babak, A., Alexei, G., Yury, G. and Alexander, S., Elastic properties of 2D $Ti_3C_2T_x$ MXene monolayers and bilayers, *Sci. Adv.*, 4(6), 0491(2018). https://doi.org/10.1126/sciadv.aat0491

Liu, G., Liu, S., Ma, K., Wang, H., Wang, X., Li, G. and Jin, W., Polyelectrolyte functionalized ti2ct x mxene membranes for pervaporation dehydration of isopropanol/water mixtures, *Ind. Eng. Chem. Res.*, 59(10), 4732-4741(2020). https://doi.org/10.1021/acs.iecr.9b06881

Liu, Y., Siyu, Z., He, J., Zhang, Z. M. and Liu, Z., Recent Progress in the Fabrication, Properties, and Devices of Heterostructures Based on 2D Materials, *Nanomicro Lett.*, 11(1), 13(2019). https://doi.org/10.1007/s40820-019-0245-5

Mehdi, A. S., Aasi, A. and Balaji, P., Experimental and Theoretical Advances in MXene-Based Gas Sensors, *ACS Omega*, 6(4), 2450-2461(2021). https://doi.org/10.1021/acsomega.0c05766

Mehranfar, A., Khavani, M. and Mohamad, I., A molecular dynamic study on the ability of phosphorene for designing new sensor for SARS-CoV-2 detection, *J. Mol. Liq.*, 345, 117852(2022). https://doi.org/10.1016/j.molliq.2021.117852

Meitong, O., Wang, X., Yu, L., Liu, C., Tao, W., Ji, X. and Mei, L., The Emergence and Evolution of Borophene, Advanced Science. 8 (2021). https://doi.org/10.1002/advs.202001801

Mirkhani, S. A., Ali, S. Z., Ehsan, A., Michael, N. and Sundararaj, U., High Dielectric Constant and Low Dielectric Loss via Poly (vinyl alcohol)/$Ti_3C_2T_x$

MXene Nanocomposites, *ACS Appl. Mater. Interf.*, 11(20), 18599-18608(2019). https://doi.org/10.1021/acsami.9b00393

Vakili, M., Cagnetta, G., Huang, J., Yu, G. and Yuan, J., 2019. Synthesis and regeneration of a MXene-based pollutant adsorbent by mechanochemical methods. *Molecules*, *24*(13),p.2478.https://doi.org/10.3390/molecules24132478

Naguib, M., Micheal, B. W. and Yury, G., Ten Years of Progress in the Synthesis and Development of MXenes, *Adv. Mater.*, 33(39), 2103393(2021). https://doi.org/10.1002/adma.202103393

Naguib, M., Saito, T., Lai, S., Rager, M. S., Tolga, A., Parans, P. M., Zhao, M. Q. and Yury, G., $Ti_3C_2T_X$ (MXene)-polyacrylamide nanocomposite films, *RSC Adv.*, 6(76), 72069-72073(2016). https://doi.org/10.1039/c6ra10384g

Natu, V. and Barsoum, M. W., Guidelines on the Intercalation of Ions and Molecules in MXenes, *Wiley*, 109-136(2024). https://doi.org/10.1002/9781119869528.ch6

Nhiem, L.T., Engineering $Ti_3C_2T_x$ (titanium carbide) MXene-based composites and emerging applications: a mini review, *RSC Adv.*, 16(27), 25116-25130(2026). https://doi.org/10.1039/d5ra08486e

Nielsen, L. E., Models for the Permeability of Filled Polymer Systems, *J. Macromol. Sci. Part A - Chem.*, 1(5), 929-942(1967). https://doi.org/10.1080/10601326708053745

Novoselov, K. S. and Geim, A. K., The rise of graphene, *Nat. Mater.*, 6(3), 183–191(2007). https://doi.org/10.1038/nmat1849

Oshima, M., Soft X-ray Nano-spectroscopy for Electronic Structures of Transition Metal Oxide Nano-structures, *Appl. Sci. Converg. Technol.*, 23(6), 317–327(2014). https://doi.org/10.5757/ASCT.2014.23.6.317

Pogorielov, M., Smyrnova, K., Kyrylenko, S., Gogotsi, O., Zahorodna, V. and Pogrebnjak, A., MXenes—A New Class of Two-Dimensional Materials: Structure, Properties and Potential Applications, *Nanomaterials*, 11(12), 3412 (2021). https://doi.org/10.3390/nano11123412

Wan, K., Li, Y., Wang, Y. and Wei, G., 2021. Recent Advance in the Fabrication of 2D and 3D Metal Carbides-Based Nanomaterials for Energy and Environmental Applications. Nanomaterials 2021, 11, https://doi.org/10.3390/nano11010246

Peng, C., Wei, P., Xin, C., Yongli, Z., Zhu, F., Cao, Y., Wang, H., Yu, H. and Peng, F., A hydrothermal etching route to synthesis of 2D MXene (Ti_3C_2, Nb_2C): Enhanced exfoliation and improved adsorption performance, *Ceram. Int.*, 44(15), 18886-18893(2018). https://doi.org/10.1016/j.ceramint.2018.07.124

Pillai, R., Balan, R., Holaday, D. and Janardhanan, J. P., Biosensing frontiers: MXenes and their composites, *Am. Chem. Soc.*, 1442, 213-236(2023). https://doi.org/10.1021/bk-2023-1442.ch009

Raghvendra, K. M., Nanostructured biomimetic, bioresponsive, and bioactive biomaterials, *Elsevier*, 35-65(2018). https://doi.org/10.1016/B978-0-08-102205-4.00002-7

Rajapakse, M., Karki, B., Abu, U. O., Sahar, P., Musa, M. R. K., Shah, R. S. M., Yu, M., gamini, S. and Jacek, J. B., Intercalation as a versatile tool for fabrication, property tuning, and phase transitions in 2D materials, *NPJ 2D Mater. Appl.*, 5(1), 30(2021). https://doi.org/10.1038/s41699-021-00211-6

Rajavel, K., Luo, S., Wan, Y., Yu, X., Hu, Y., Zhu, P., Sun, R. and Wong, C., 2D Ti3C2Tx MXene/polyvinylidene fluoride (PVDF) nanocomposites for attenuation of electromagnetic radiation with excellent heat dissipation, *Compos. Part A Appl. Sci. Manuf.*, 129, 105693(2020). https://doi.org/10.1016/j.compositesa.2019.105693

Ranjan, P., Sahu, T. K., Rebti, B., Srkc, S. Y., Late, D. J., Kumar, P. and Vinu, A., Freestanding Borophene and Its Hybrids, *Adv. Mater.*, 31(27), 1900353(2019). https://doi.org/10.1002/adma.201900353

Ren, C. E., Hatzell, K. B., Alhabeb, M., Ling, Z., Mahmoud, K. A. and Gogotsi, Y., Charge-and size-selective ion sieving through $Ti_3C_2T_x$ MXene membranes, *J. Phy. Chem. Lett.*, 6(20), 4026-4031(2015). https://doi.org/10.1021/acs.jpclett.5b01895

Roy, K., Medini, P., Srijit, G., Sai, T. P., Ramalingam, G., Srinivasan, R. and Ghosh, A., Graphene–MoS2 hybrid structures for multifunctional photoresponsive memory devices, *Nat. Nanotechnol.*, 8(11), 826–830(2013). https://doi.org/10.1038/nnano.2013.206

Sarycheva, A. and Yury, G., Raman Spectroscopy Analysis of the Structure and Surface Chemistry of $Ti_3C_2T_x$ MXene, *Chem. Mater.*, 32(8), 3480-3488(2020). https://doi.org/10.1021/acs.chemmater.0c00359

Sarycheva, A., Shanmugasundaram, M., Krayev, A. and Gogotsi, Y., Tip-enhanced Raman scattering imaging of single-to few-layer Ti3C2Tx MXene, *ACS nano*, 16(4), 6858-6865(2022). https://doi.org/10.1021/acsnano.2c01868

Shah, A. A., Hasan, F., Hameed, A. and Ahmed, S., Biological degradation of plastics: A comprehensive review, *Biotechnol. Adv.*, 26(3), 246–265(2008). https://doi.org/10.1016/j.biotechadv.2007.12.005

Sheng, X., Zhao, Y., Li, Z. and Lu, X., Properties of two-dimensional Ti_3C_2 MXene/thermoplastic polyurethane nanocomposites with effective reinforcement via melt blending, *Compos. Sci. Technol.*, 181, 107710(2019). https://doi.org/10.1016/j.compscitech.2019.107710

Shi, Y., Liu, C., Liu, L., Fu, L., Yu, B., Lv, Y., Yang, F. and Song, P., Strengthening, toughing and thermally stable ultra-thin MXene nanosheets/polypropylene nanocomposites via nanoconfinement, *Chem. Eng. J.*, 378, 122267(2019). https://doi.org/10.1016/j.cej.2019.122267

Sivasankarapillai, V. S., Sharma, T. S. K., Hwa, K. Y., Saikh, W. M., Subramania, A. and Ragupathy, D., MXene Based Sensing Materials: Current Status and Future Perspectives, *ES Energy Environ*., (2022). https://doi.org/10.30919/esee8c618

Siwal, S. S., Karamveer, S., Kirti, M., Kaur, H., Saini, A. K., Vipin, S., Vo, D. V. N., Hamed, N. Y. and Thakur, V. K., Novel synthesis methods and applications of MXene-based nanomaterials (MBNs) for hazardous pollutants degradation: Future perspectives, *Chemosphere*, 293, 133542(2022). https://doi.org/10.1016/j.chemosphere.2022.133542

Stajic, J., Dirac cones in a boron monolayer, *Sci*., 355(6331), 1278.7-1279(2017). https://doi.org/10.1126/science.355.6331.1278-g

Sun, R., Zhang, H. B., Liu, J., Xie, X., Yang, R., Li, Y., Hong, S. and Yu, Z. Z., Highly Conductive Transition Metal Carbide/Carbonitride (MXene)@polystyrene Nanocomposites Fabricated by Electrostatic Assembly for Highly Efficient Electromagnetic Interference Shielding, *Adv. Funct. Mater*., 27(45), 1702807(2017). https://doi.org/10.1002/adfm.201702807

Taloub, N., Henniche, A., Liu, L., Li, J., Nahla, R., Mohammad, H. and Huang, Y., Improving the mechanical properties, UV and hydrothermal aging resistance of PIPD fiber using MXene ($Ti_3C_2(OH)_2$) nanosheets, *Compos. B Eng*., 163, 260-271 (2019). https://doi.org/10.1016/j.compositesb.2018.11.007

Thakur, A., Kim, J., Wyatt, B. C., Gogotsi, Y. and Anasori, B., Composition–structure–property relationships in MXenes, *Nat. Rev. Mater*., 11(7), 516-531(2026). https://doi.org/10.1038/s41578-026-00911-9

Tripathy, D. B. and Pradhan, S., MXenes-polymer nanocomposites: sustainable solutions for biomedical applications, *Int. J. Polym. Mater. Polym. Biomater*., 75(1), 23-48(2026). https://doi.org/10.1080/00914037.2025.2493919

Tu, S., Qiu, J., Zhang, X. and Husam, A. N., Large Dielectric Constant Enhancement in MXene Percolative Polymer Composites, *ACS Nano*., 12(4), 3369-3377 (2018). https://doi.org/10.1021/acsnano.7b08895

Ullah, S., Najam, T., ur Rehman, A., Alarfaji, S.S., Ahmad, M.A., Riaz, S., Akkinepally, B., Shah, S.S.A. and Nazir, M.A., MXene nanomaterials: Synthesis, properties and applications in energy and environment sector, *J. Alloys Compd*., 1001, 175172 (2024). https://doi.org/10.1016/j.jallcom.2024.175172

Urbankowski, P., Anasori, B., Hantanasirisakul, K., Yang, L., Zhang, L., Haines, B., May, S. J., Billinge, S. J. and Gogotsi, Y., 2D molybdenum and vanadium nitrides synthesized by ammoniation of 2D transition metal carbides (MXenes), *Nanoscale*, 9(45), 17722-17730(2017). https://doi.org/10.1039/c7nr0672.1f

Vaia, R. A., Ali, J., Asra, H., Neher, G., Nepal, D., Ruth, P., Joshua, K. W. and Subramanian, R., Halogen etch of Ti_3AlC_2 MAX phase for mxene fabrication, *ACS Nano*., 15(2), 2771-2777(2021). https://doi.org/10.1021/acsnano.0c08630

Vogel, E. M. and Joshua, R. A., Two-dimensional layered transition-metal dichalcogenides for versatile properties and applications, *MRS Bull*., 40(7), 558–563(2015). https://doi.org/10.1557/mrs.2015.120

Wang, L., Hua, Q., Song, P., Yali, Z., Lu, Y., Liang, C., Kong, J., Chen, L. and Gu, J., 3D $Ti_3C_2T_x$ MXene/C hybrid foam/epoxy nanocomposites with superior electromagnetic interference shielding performances and robust mechanical properties, *Compos. Part A Appl. Sci. Manuf*., 123, 293-300(2019). https://doi.org/10.1016/j.compositesa.2019.05.030

Wassei, J. K. and Kaner, R. B., Graphene, a promising transparent conductor, *Mater. Today*, 13(3), 52–59(2010). https://doi.org/10.1016/S1369-7021(10)70034-1

Wei, Y., Peng, Z., Razium, S. A., Zhu, Q. and Xu, B., Advances in the Synthesis of 2D MXenes, *Adv. Mater*., 33(39), 2103148(2021). https://doi.org/10.1002/adma.202103148

Xin, M., Li, J., Ma, Z., Pan, L. and Shi, Y., MXenes and Their Applications in Wearable Sensors, *Front. Chem*., 8, 297(2020). https://doi.org/10.3389/fchem.2020.00297

Yankowitz, M., Xue, J. and LeRoy, B. J., Graphene on hexagonal boron nitride, *J. Phy. Condensed Matter*., 26, 303201 (2014). https://doi.org/10.1088/0953- 8984/26/30/303201

Yazdanparast, S., Sina, S., Annika, F. W., Tucker, G. J. and Geoff, L. B., Synthesis and Surface Chemistry of 2D TiVC Solid-Solution MXenes, *ACS Appl. Mater. Interf*., 12(17), 20129-20137 (2020). https://doi.org/10.1021/acsami.0c03181

Ying, Y., Liu, Y., Wang, X., Mao, Y., Cao, W., Hu, P. and Peng, X., Two-dimensional titanium carbide for efficiently reductive removal of highly toxic chromium (VI) from water, *ACS Appl. Mater. Interf.*, 7(3), 1795-1803(2015). https://doi.org/10.1021/am5074722

Yoon, J., Shin, M., Lim, J., Lee, J. Y. and Choi, J. W., Recent advances in MXene nanocomposite-based biosensors, *Biosens*., 10(11), 185(2020). https://doi.org/10.3390/bios10110185

Zamhuri, A., Lim, G. P., Ma, N. L., Tee, K. S. and Soon, C. F., MXene in the lens of biomedical engineering: synthesis, applications and future outlook, *Biomed. Eng. Online*., 20(1), 33(2021). https://doi.org/10.1186/s12938-021-00873-9

Zhang, J., Liu, Y., Lv, Z., Zhao, T., Li, P., Sun, Y. and Wang, J., Sulfonated $Ti_3C_2T_x$ to construct proton transfer pathways in polymer electrolyte membrane for enhanced conduction, *Solid State Ion*, 310, 100-111(2017). https://doi.org/10.1016/j.ssi.2017.08.013

Zhang, L., Song, W., Liu, H., Ding, H., Yan, Y. and Chen, R., Influencing factors on synthesis and properties of MXene: a review, *Processes*, 10(9), 1744(2022).
https://doi.org/10.3390/pr10091744

Zhao, X., Zha, X. J., Tang, L. S., Pu, J. H., Ke, K., Bao, R. Y., Liu, Z. Y., Yang, M. B. and Wei, Y., Self-assembled core-shell polydopamine@MXene with synergistic solar absorption capability for highly efficient solar-to-vapor generation, *Nano Res.*, 13(1), 255-264(2020).
https://doi.org/10.1007/s12274-019-2608-0

Zheng, Z., Guo, C., Wang, E., He, Z., Liang, T., Yang, T. and Hou, X., The oxidation and thermal stability of two-dimensional transition metal carbides and/or carbonitrides (MXenes) and the improvement based on their surface state, *Inorg. Chem. Front.*, 8(9), 2164-2182(2021).
https://doi.org/10.1039/d1qi00041a