

**Review Article****New wonder materials - exciting technological horizon**

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**ABSTRACT**

A significant advancement in materials science has been made with the 2D MXene nanomaterials that were etched from their parent 3D MAX phases. Layered ternary carbide, nitride, and boride compounds with the general formula  $M_{n+1}AX_n$  ( $n=1,2, 3,4 \dots$ ) make up the 3D MAX phase materials, where A is an element of Group IIA or IIIA, M is an early transition metal, and X is either C, N, or B. MXene's chemical formula is  $M_{n+1}X_n$ , whereas that of the precursor is  $M_{n+1}AX_n$ . The MAX materials have a distinct set of properties that are similar to those of metal and ceramic. They are helpful in the development of high-efficiency engines, thermal systems that can withstand damage, fatigue resistance enhancement, and high-temperature rigidity retention technologies. The 2D MXenes are potentially described as a 'wonder material' in the class of nanomaterials. Because of their intriguing mechanical properties resulting from their atomically thin dimensions, as well as their unusual electrical and optical properties, these have become the focus of materials research in recent years. These nanomaterials are multilayer electrically conductive materials that are comparable to multilayer graphene. They have been discovered to be beneficial for a variety of applications, such as energy storage materials, composite reinforcement, chemical, environmental, and biological sensors, and electronic devices. The recent advancements in the use of nanomaterials in optoelectronics, field-effect transistors, transparent conductive electrodes and shielding against electromagnetic interference, energy storage, and other fields have been extensively documented. The potential of nanomaterials as a novel ceramic photothermal agent employed in cancer therapy has been revealed by a very recent study on  $Ti_3C_2$  MXene. The same 2D nanomaterial can be used in water desalination and purification membranes since it has antibacterial qualities and is resistant to bio fouling. The MXene-based piezoresistive sensor is also capable of detecting weak pressures and the slight bending-release actions of humans. It can be applied to recover lost frictional energy from, say, walking or typing-related muscular contractions. Since MAX phases are precursors to MXenes, the former are valuable due to the growing interest in the latter. This review provides an overview of the literature, including the author's own work, from the groundbreaking MXene publication to the present. It provides information on the characteristics, synthesis, crystal structure, and current and future uses of the new wonder materials as well as the MAX phases.

**Introduction**

Today's technological advancements dictates the search for new nanomaterials for a wide range of applications, including energy storage, optoelectronics, and medicine. An atom from the group of early transition metals and an

atom from A-group elements (Al, Si, etc.) chemically combine with carbon or nitrogen or boride to give rise to a new type of compounds known as MAX phases. There is a technique to eliminate A-group element, mainly

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Al from the MAX phase to form exfoliated layered structured MXene, which creates a potential role in many applications. Recent years have seen a significant increase in interest in both the 3D MAX materials and the derived 2D MXene materials due to their exceptional mechanical, chemical, and physical qualities as well as their wide range of potential applications.

MAX phases are new ceramics with a layered structure that are both structural and functional. MAX phases are exfoliated to create 2D materials called MXenes, which have structures like graphene. MXene materials have a high specific surface area, good chemical stability, biocompatibility, tunable physical properties, and other characteristics that allow their surface to interact with more functional atoms and molecules. The MAX phase is typically etched, among other techniques, in the preparation of MXene materials. Physical qualities including electrical conductivity, magnetism, and optics can be tuned by varying the chemical composition and structure of MXene materials. These wonder materials through their current exciting applications and prospects for future applications show promising technological horizon, e.g. among others in the delivery of drug, treatment of cancer etc., which are popular topics these days.

### MAX phase materials

The 3D MAX phase materials are layered ternary carbide, nitride and boride nanolaminated compounds with general formula  $M_{n+1}AX_n$  ( $n = 1, 2, 3, 4 \dots$ ), where M is an early transition metal, A is a Group IIA or IIIA element and X is C, N, B and/or P. While the precursor has  $M_{n+1}AX_n$  chemical formula MXene has  $M_{n+1}X_n$  formula. The number of phases has expanded from the initial 50 or so to over 300 in recent years due to advancements in phase research. Following 2018, half of the 342 MAX phases were found. At the moment, alloys including 28 M, 28 A, and 6 X elements have been integrated into the MAX phases. Furthermore, using phase stability predictions 182 new theoretically stable MAX phases are awaiting experimental confirmation, according to Dahlqvist et al. (2024). Notably, MAX phases are even more important because they are predecessors to MXenes, and there is a growing interest in the latter due to a wide range of possible uses.

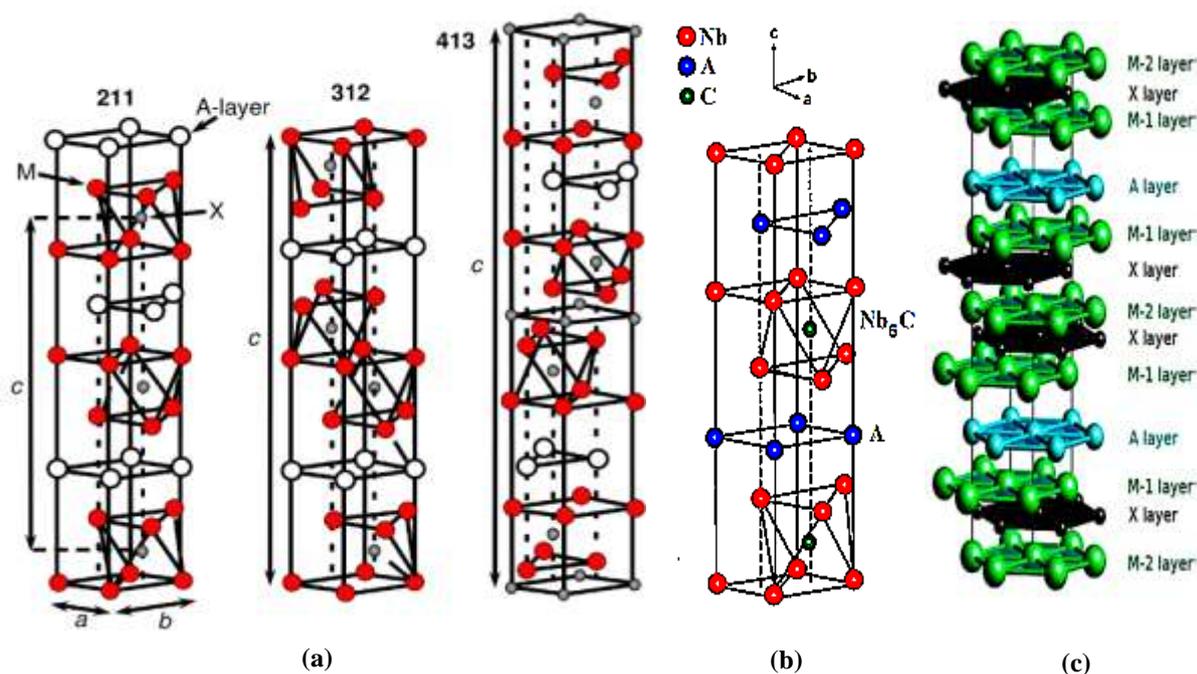
The MAX materials possess unique set of both ceramic- and metal-like properties. They are useful in technologies involving high efficiency engines, damage tolerant thermal systems, increasing fatigue resistance, and retention of rigidity at high temperatures.

### Discovery of MAX phases

MAX phases were discovered first by crystal chemist Hans Nowotny and his coworkers during the 1960s. The phases, called H-phases at that time, included more than thirty 211 phases ( $Ti_2AlC$ ,  $Ti_2AlN$ ,  $V_2AlC$ , etc.) and two 312 phases ( $Ti_3SiC_2$  and  $Ti_3GeC_2$ ) (Jeitschko et al., 1963; Jeitschko and Nowotny 1967; Jeitschko et al., 1964). In the 1980s, another important 312 phase,  $Ti_3AlC_2$ , was found by Schuster and Nowotny (1980).

However, until the mid1990s, these MAX phases received little attention from the scientific community because of their unstable and impure performance. Predominately single-phase, dense samples of  $Ti_3SiC_2$  were prepared by Barsoum and his group at Drexel University in 1996 and their mechanical and oxidation behaviors were evaluated (Barsoum et al., 1997). Later, several bulk MAX phases ( $Ti_2AlC$ ,  $V_2AlC$ ,  $Ti_2SnC$ ,  $Nb_2AlC$ , etc.) were fabricated successfully by them and it was observed that they possessed similar properties like those of  $Ti_3SiC_2$  (Barsoum and El-Raghy, 1996). Barsoum et al. (1999) further discovered  $Ti_4AlN_3$  in 1999, which yields the first prototype of 413 phase and led to the the formula  $M_{n+1}AX_n$  or MAX for short.

The ternary phases typically crystallize in space group  $P6_3/mmc$  and follow the notation  $M_{n+1}AX_n$  for describing their stoichiometry (Fig. 1). Commonly used short notations for composition are: 211 ( $n = 1$ ) for  $M_2AX$ , 312 ( $n = 2$ ) for  $M_3AX_2$ , 413 ( $n = 3$ ) for  $M_4AX_3$  etc.  $M_{n+1}X_n$  layers with ceramic properties are formed in the crystal structure of MAX phases by the near-closed packing of M atoms and the X atoms filling the edge-shared  $M_6X$  octahedral sites. A layers with metal properties separate the  $M_{n+1}X_n$  layers. MAX phases thus combine the metal and ceramic properties. Like metals, MAX phases have high strength, excellent high temperature strength, and thermal stability. They are also easily machined with conventional tools, thermally and electrically conductive, and resistant to thermal shock (Zhou et al. 2021).



**Fig. 1.** Several ternary MAX phase structures. (a) Conventional phases crystallize in space group  $P6_3/mmc$  with a general  $M_{n+1}AX_n$  composition. (b) Hexagonal crystal structure of  $Nb_2AC$  (A: Al, S, Ge, As, and Sn), in which A atomic sheets are sandwiched between blocks of Nb-carbides  $[Nb_6C]$  formed by edge-shared  $Nb_6C$  octahedra. (c) Crystal structure of the 312 MAX phase (Fillipatos et al., 2019). For the 312 structure, there are two different M sites denoted M-1 and M-2.

### Superconducting MAX phases

In 1967  $Mo_2GaC$  was the first MAX phase to exhibit superconducting characteristics with transition temperature  $T_c \sim 4.0$  K (Toth, 1967). According to the BCS theory, superconductivity is attributed to a phonon-mediated attraction between mobile electrons near Fermi surface (called Fermi electrons). The attraction is sometimes referred to as a residual Coulomb interaction that can glue Cooper pair together to cause superconductivity. MAX materials are expected to be possible superconductors because of the metallic-like characteristics of the phases. Indeed in such remarkable class of materials there are ten low-temperature superconductors studied from about 70 MAX phases reported till 2015 (Islam, 2021, Hadi et al., 2014; Hadi et al., 2013, Karaca et al., 2021). The superconducting transition temperatures ( $T_c$  in K) of the experimentally proven MAX superconductors along with their theoretically

obtained parameters are presented in Table 1. The number of reported superconductors shows that a vast majority of the MAX phases are not superconductors and all superconducting MAX phases belong to the 211 subfamily of MAX phases. The reason is due to the difference in repetition of the A-layers, the 211 structure has more metallic and better electrical and thermal conducting properties than the 312 and 413 phases that have more carbide- or nitride-like properties (Magnuson and Mattesini, 2017).

The conductivity, elasticity, magnetism, and other material properties can be altered by changing the elements at the M, A, or X-sites in the crystal structure. This allows for the manipulation of the chemical bond strengths, which in turn allows for the customization of this class of materials' properties (Magnuson and Mattesini, 2017).

**Table 1. DOS at the Fermi level ( $N_F$  in states/eV), frequency ( $\omega_{ln}$  in K), the average e-ph coupling constant ( $\lambda$ ), and  $T_c$  (K) for the MAX phases. E= Expt. T= Theoret.**

MAX	$N(E_F)$ (states/eV)	$\omega_{ln}$ (K)	$\lambda$	$T_c$ (K)	References
Nb <sub>2</sub> SC	3.452	249.124	0.739 <sup>T</sup>	7.72 <sup>T</sup>	Karaca et al., 2021
				7.78 <sup>E</sup> , 7.2 <sup>E</sup>	Bortolozza et al., 2006, Romero et al., 2013
				5.0 <sup>E</sup>	Sakamaki et al., 1999
Nb <sub>2</sub> GeC	3.992	298.347	0.685 <sup>T</sup>	9.83 <sup>T</sup>	Karaca et al., 2021
				10.0 <sup>E</sup>	Bortolozza et al., 2017
Nb <sub>2</sub> AsC	3.005	300.906	0.44 <sup>T</sup>	2.09 <sup>T</sup>	Karaca et al., 2021
				3.00	0.34 <sup>E</sup>
Nb <sub>2</sub> SnC	3.843	258.14	0.614 <sup>T</sup>	6.31 <sup>T</sup>	Karaca et al., 2021
				7.8 <sup>E</sup> , 7.2 <sup>E</sup>	Bortolozza et al., 2006, Romero et al., 2013
Nb <sub>2</sub> InC	-	-	-	7.5 <sup>E</sup>	Bortolozza et al., 2009
Mo <sub>2</sub> GaC	4.79	-	-	4 <sup>E</sup>	Toth, 1967
Ti <sub>2</sub> InN	-	-	-	7.3 <sup>E</sup>	Bortolozza et al., 2010
				0.62 <sup>T</sup>	-
Ti <sub>2</sub> InC	-	-	-	3.1 <sup>E</sup>	Bortolozza et al., 2007
				0.49 <sup>T</sup>	-
Ti <sub>2</sub> GeC	-	-	-	9.5 <sup>E</sup>	Bortolozza et al., 2012
Lu <sub>2</sub> SnC	-	-	-	5.2 <sup>E</sup>	Kuchida et al., 2013
Ti <sub>2</sub> AlN	-	-	-	13 <sup>T</sup>	Karaca et al., 2022

The structural parameters, elastic, electronic, thermodynamic and optical properties of the MAX superconductors have been studied by several researchers. Variety of such theoretical and experimental studies have revealed the structural, electronic, mechanical and vibrational, thermodynamic, thermal, magnetic, transport and optical properties including machinability, brittle/ductile behavior, radiation resistance and damage tolerance of the materials (Shein and Ivanovskii., 2010, 2011; Nasir and Islam, 2012; Hadi et al., 2013; Roknuzzaman

and Islam, 2013; Hadi et al., 2014; Hadi et al., 2019; Karaca et al., 2021).

The transition temperatures  $T_c$  of hexagonal Nb<sub>2</sub>AC (A: Al, S, Ge, As and Sn) have been studied using DFT (perturbation) to model the e-ph interaction (Karaca et al., 2021). These theoretical results - DOS at the Fermi level  $N_F$ , logarithmic frequency  $\omega_{ln}$ , the average e-ph coupling constant  $\lambda$  and the superconducting transition temperature  $T_c$  are also shown in the table for comparison with the experimental  $T_c$ .

## Magnetic MAX phases

DFT was first used to predict magnetic MAX phases by evaluating phase stability. These were then synthesized as heteroepitaxial thin films. A nanolaminated magnetic MAX compound which has only one M-element, namely  $\text{Mn}_2\text{GaC}$  was predicted theoretically and subsequently synthesized first by Ingason et al. (2014). According to Ingason et al. (2016), all magnetic MAX phases that have been described thus far, whether in bulk or thin-film form, are based on Cr and/or Mn. The list includes  $(\text{Cr,Mn})_2\text{AlC}$ ,  $(\text{Cr,Mn})_2\text{GeC}$ ,  $(\text{Cr,Mn})_2\text{GaC}$ ,  $(\text{Mo,Mn})_2\text{GaC}$ , and  $(\text{V,Mn})_3\text{GaC}_2$ ,  $\text{Cr}_2\text{AlC}$ ,  $\text{Cr}_2\text{GeC}$  and  $\text{Mn}_2\text{GaC}$ .

Numerous magnetic characteristics have been discovered, including structural alterations connected to magnetic anisotropy and ferromagnetic reactivity much above room temperature. The techniques, findings, and conclusions of the theoretical and experimental work done on these materials up to this point are critically examined by Ingason et al. (2016). An outlook centered on new materials, superstructures, property tailoring, and more synthesis and characterization is offered, along with questions about magnetic properties that are examined.

The discovery of novel magnetic phases and compositions, as well as the foundations of magnetic properties, have been the exclusive focus of research efforts thus far. However, potential uses have been noted thus far for everything from refrigeration to spintronics (Ingason et al., 2016).

## Synthesis, properties and applications

### Synthesis

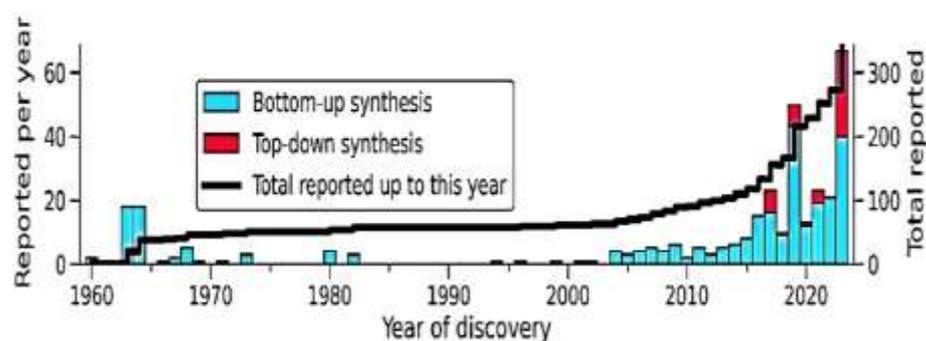
Many techniques for bulk solid-state synthesis have been developed to yield a range of MAX phases. However, since 2002, there has been a growing interest in potential applications due to the growth of MAX phases, particularly in its high quality epitaxial thin-films form (Palmquist et al., 2002).

Among these are bond coatings on sapphire fibers, low friction and oxidation-resistant contacts, and

protective and oxidation-resistant coatings for turbine blades. In the latter cases, the main objective is to produce high density single-phase films, and since 2010, most efforts have been made to produce single crystal samples of superior quality. Chemical vapor deposition (CVD), magnetron sputtering, cathodic arc deposition, and pulsed laser deposition (PLD) are the primary growth techniques that have been employed for the deposition of MAX phases thin films. Biswas et al. (2021) have provided an overview of the advancements achieved thus far in the assessment of the properties and epitaxial growth of MAX phase thin films cultivated using diverse deposition methods. Dahlqvist et al. (2024) published a review paper in which MAX phase classification based on their synthesis method was introduced (Fig. 2). The distinct elemental compositions of the two synthesis routes, bottom-up and top-down, inspired the idea of dividing the MAX phases according to how they were synthesized. Adding magnetic elements and noble metals to the A-layer of MAX phases via top-down synthesis is a sophisticated method of creating more exotic MAX phases. We would now go over to their classification system.

### Bottom-up synthesis

The first category consists of the 'classic' MAX phases with space group  $P6_3/mmc$ . A is an element of the A-group (groups 12 to 16), M is the early transition metal, and X is C, N, B and/or P. In this case, 'classic' does not imply 'old', but rather refers to Nowotny's discoveries, where  $n = 1, 2, 3$ , and so on to 4, 5, or 6. Similarly, for recent discoveries of B-containing MAX phases (Rackl et al., 2019). The ability to be created directly through synthesis, for example, by thin film deposition or powder metallurgy routes (powder synthesis) (Dahlqvist et al., 2024) is another significant characteristic of bottom-up synthesized MAX phases. Accordingly, this group comprises high-entropy MAX phases and ternary MAX phases, as well as matching alloys that go up to multi-element solids with significant disorder on the M-sites (Dahlqvist et al., 2024), provided that they can be synthesized in a single step and follow the hexagonal  $P6_3/mmc$  space group symmetry.



**Fig. 2. Discovery histogram for synthesized MAX phases. Credit: Permission from Dahlqvist et al. (2024). Copyright © 2023 The Authors. Published by Elsevier Ltd.**

### Top-down synthesis

The only difference between this one and the first category is that we now include A-site elements outside of groups 12 to 16 (Dahlqvist et al., 2024). The modification of the A-group layers is what distinguishes a top-down synthesized MAX phase from other types. This is more important than its chemistry. These phases are typically obtained through post-synthesis procedures from a bottom-up MAX phase precursor in which the A-layer is either partially or completely replaced. Here, we discuss two approaches:

1. the molten salt method, which substitutes a more varied group of elements, such as transition metals like Mn, Fe, Co, Ni, Cu, Zn, (Li et al., 2019) and
2. the replacement of noble metals in MAX phase thin films by thermally induced exchange reactions, e.g. Al, Si, and Ga layers with layers of Au or Ir. In-plane order within the A-layers among top-down synthesized phases is also found (Lai et al., 2017).

### Properties and application

Physical and chemical characteristics of MAX phases is provided here. In fact a very brief survey is discussed on the possible domains of use of MAX phases, including MXene precursors, nuclear materials, and materials at high temperatures.

Interesting characteristics of MAX phase compositions include oxidation resistance, damage tolerance, crack healing, machinability, irradiation tolerance, relatively high temperature stability, and

resistance to liquid metal corrosion. They are suitable options for electrical contacts, sensors, connectors, etc. because of their good electrical and thermal properties. Furthermore, some of the MAX phases are used in protective coatings, micro-mechanical systems, and even commonplace items like drill bits and non-stick cookware because of their superior mechanical properties. Ultimately, they are good options for high-temperature structural and non-structural applications, such as gas burning and heating elements, due to their exceptional high temperature properties and resistance to oxidation (Barsoum, 2013).

#### a. Fracture toughness and damage tolerance

One important characteristic that gauges a material's resistance to crack propagation is fracture toughness. It sheds light on a material's capacity to tolerate the propagation of pre-existing fissures under stress. In general, ceramic materials exhibit brittle mechanical properties. They do not have energy-absorbing systems like dislocation motion of metals. As a result, most ceramics have a modest fracture toughness ( $K_{IC}$ ) due to their low resistance to crack propagation. However, this characteristic is required for designing a structural component in the majority of engineering applications, which restricts the usage of ceramic materials. The inclusion of extra energy-absorbing processes, which may make MAX phase materials several times harder than their comparable binary carbides, is one of their distinctive characteristics. The damage resistance mechanism is related to the fact that it is nanolayered, but this structure alone cannot explain it (Goossens et al., 2021).

## b. Oxidation resistance and crack healing

Some MAX phases possess excellent oxidation resistance (Goossens et al., 2021). The formation of a protective oxide layer that adheres well to the underlying material is essential for the material's stability in oxidative environments. MAX phase compounds that exhibit strong resistance to oxidation (i.e. stable above 1000°C) are  $Ti_3SiC_2$ ,  $Ti_2AlC$ ,  $Ti_3AlC_2$ , and  $Cr_2AlC$ .  $Ti_3SiC_2$  exhibits a stable oxidation behavior up to roughly 1100°C, forming a duplex oxide layer consisting of an outer rutile ( $TiO_2$ ) layer followed by a mixture of  $TiO_2$  and silica ( $SiO_2$ ) (Barsoum et al., 1997; Sun et al., 2001). The three additional compounds primarily depend on the creation of a stable layer of  $\alpha-Al_2O_3$ . Tallman et al. (2013) provide a thorough overview of their oxidation behavior in which the most oxidation-resistant MAX phase is said to be  $Ti_2AlC$ .

The capacity of MAX phases to 'heal' cracks has been demonstrated by research on their oxidation behavior in the Ti-Al-C system. In order to partially restore the material's strength,  $Ti_2AlC$  or  $Ti_3AlC_2$  must be heat treated in an oxidative environment to produce  $TiO_2$  and  $Al_2O_3$  oxidation products that fill the crack (Song et al., 2016; Yang et al., 2011).

## c. Corrosion and radiation resistance

The candidate structural/functional MAX phase based materials for some applications in the Gen-IV lead-cooled Fast Reactor (LFR) must be compatible with the heavy liquid metal (HLM) primary coolant, such as lead (Pb) and lead-bismuth eutectic (LBE) (Goossens et al., 2021).

Under operational circumstances where traditional stainless steels are severely hampered by dissolution corrosion (Lambrinou et al., 2017) in contact with liquid LBE, most MAX phases remain inert due to factors like high temperatures (> 450°C) and low HLM oxygen concentrations (<10 mass%).

$M_{n+1}AX_n$  phases due to their unusual characteristics have been proposed for application in both fission and fusion nuclear reactors, where they will be subjected to high temperatures and harsh radiation conditions. The electronic structures, bonding types, and defect processes of Sn-based 211 MAX phases

have been studied by Hadi et al. (2019). A detailed theoretical study of the intrinsic defect processes,  $Nb_2SnC$  is predicted to have better radiation tolerance of the  $M_2SnC$  MAX phases ( $M = Lu, Ti, Zr, Hf, Nb$ ). A more or less similar studies of a newly synthesized 211 MAX phase  $V_2SnC$  has been made by Hadi et al. (2020). The new phase  $V_2SnC$  when included in the systems of 5-member of Sn-based 211 MAX phases,  $Nb_2SnC$  remains in the same position. Compared to the other  $M_2SnC$  phases, the radiation resistance of  $V_2SnC$  is better than  $Lu_2SnC$  and lower than the remaining phases.

The effects of radiation on the  $M_{n+1}AX_n$  phases have recently been the subject of numerous other studies, which have revealed complex behavior induced by ion or neutron irradiation over a range of temperatures, including phase transformations, surface modification, and mechanical property changes. Wang et al. (2020) examine the intrinsic controls on the radiation tolerance of these materials and summarize recent experimental and theoretical work on the response of the  $M_{n+1}AX_n$  phases to irradiation. This article develops a thorough understanding of the mechanisms underlying the structural modification and defect evolution caused by irradiation in  $M_{n+1}AX_n$  phases. It also suggests strategies for creating new  $M_{n+1}AX_n$  phases that perform better under extreme irradiation scenarios.

## d. Stability at elevated temperature

Transition metal carbides are referred to as refractory carbides because of their superior strength at elevated temperatures. It has been reported that the MAX phases exhibit good stability at high temperatures. Phase stability is the primary lens through which to interpret this thermal stability. The MAX phases separate at high temperatures, and depending on the particular MAX phase and the surrounding circumstances, the precise dissociation temperature can range from roughly 1000°C to 1700°C. Low (2019) published a summary of the various factors influencing the breakdown and deterioration of Ti-based MAX phases.

The mechanical behavior of the MAX phases under high temperature and mechanical loads is also of interest. The current state of knowledge on this

mechanical behavior is based mainly on experiments with  $Ti_2SiC_2$ , with some reports on  $Ti_2GeC_2$  and Al containing phases. A detailed description can be found in Barsoum (2013). Generally speaking, MAX phases have a BPTT (Brittle-to-Plastic transition temperature).

#### **e. Machinability**

The machinability of MAX phase compounds is a key technical feature for the manufacturing and shape of components. Because they can be machined with standard high-speed steel and hard metal tools, shaping of the MAX phases can be accomplished with traditional machining techniques including milling, turning, and drilling. As oxide or carbide phases that are parasitic might harm the tools, excellent phase purity is an essential requirement for machining.

### **MXenes**

#### **Introduction**

2D materials are among the most interesting scientific research materials of the 21st century. The 'First Wonder Material' is 2D Graphene which was discovered in 2004 for which 2010 Nobel Prize was awarded to Andre Geim and Kostya Novoselov both of the University of Manchester. It is considered as a miracle material for scientists and engineers owing to its outstanding physical properties. Graphene and its nano-composites are promising multifunctional materials with improved tensile strength and elastic modulus.

MXenes are potentially described as a 'wonder material' in the class of 2D nanomaterials. These 2D-layered MXenes, mostly derived from MAX phases, have the suffix 'ene' to indicate that they are similar to grapheme. The credit for the groundbreaking discovery in 2011 goes to researchers led by Yury Gogotsi and Michel Barsoum at Drexel University, USA. They achieved this feat by selectively etching the A layer from bulk MAX phases, resulting in the creation of multilayered MXenes. (Naguib et al., 2011; Naguib et al., 2012). The fields of MXene development, synthesis, and application are expanding quickly. This material family has demonstrated superior performance compared to materials utilized in numerous applications and holds

the potential to revolutionize the integration of nanotechnology in daily life (MXenes, Drexel Nanomaterials Institute). Ever since the discovery of the first MXene in 2011, about 40 MXenes have been successfully synthesized, with many of these originating from Linköping University, Sweden, and many more are predicted till date.

MXenes are a fascinating class of materials that have captured the imagination of scientists and their efforts continue to unfold as researchers delve deeper into their properties and applications. The flurry of scientific activity on MXenes has been remarkable. Not seen since the discovery of Graphene was there such a proliferation of research articles and intense interest in a class of materials in such a short period of time. From fundamental properties to applications in batteries, catalysis, optoelectronics, medicine and telecommunications, MXenes have had a meteoric rise in materials science.

MXene is considered superior to graphene because MXene is inherently hydrophilic, yet exhibits higher conductivity than solution-treated graphene (Dillon et al., 2016). Furthermore, their remarkable electrochemical characteristics hold significant potential for flexible electronics and planar devices.

Since 2015, MXenes research has grown significantly on a worldwide scale, with more publications, including many groundbreaking papers, coming from countries other than the USA. Approximately 70,000 scientists from over 7600 institutions across 100 countries on all six continents have done MXene research so far. Since that this statistic is based on data from the Web of Science, which has a high barrier for adding publications to the database, the total numbers are believed to be 20-30% higher. (Anasori and Gogotsi, 2023). So MXenes global expansion may further be realized if one checks the holding of conferences in 2024 only. The third MXene conference, which will take place at MXenes' birthplace of Drexel University in Philadelphia, PA, on August 5-7, 2024, is planned. It is anticipated that Xi'an, China will host the Fifth International Conference on MXenes in October 2024. The first MXene conference specifically in Europe, called EUROMXENE, is likewise slated for June 2024 in Valencia.

### Brief review of synthesis of MXenes

Naguib et al. (2011; 2012) developed and reported the synthesis of MXene phases. The 2D layers that remain after the A group layer is removed from the MAX phases are called MXenes to signify the absence of the A element and highlight their structural resemblances to graphene.

The family of 2D transition metal carbides, nitrides, and carbonitrides (MXenes) has grown significantly since the initial publication on  $Ti_3C_2T_x$  in 2011.

MXenes now comprise both single and multi-element compounds, and many more have not yet been synthesized but are expected to have desirable features. A more thorough mechanistic knowledge of the precursors, etching-exfoliation, and final intercalation-delamination stages of the known MXene synthesis methods is required in order to synthesize these elusive compounds as well as to enhance and increase the production of known MXenes (Lim et al., 2022).

There are now two distinct methods for obtaining MXenes through the 'bottom-up' and 'top-down' ways (Fig. 3). The primary distinction between these two approaches is that, whereas the bottom-up technique forms the material from the bottom to the top using MXene deposition technology, the top-down synthesis method separates bulk materials, like

MAX phases into several layers. It should be noted that the characteristics of the MXenes might vary depending on the synthesis process used. Moreover, the starting material including non MAX layered materials and different surface modification techniques employed in their preparation determine the properties of 2D transition metal Carbides/nitrides/carbonitrides etc. For more details and to identify the advantages and disadvantages of various strategies see the review articles (Pogorielov et al., 2021; Lim et al., 2022; Panda et al., 2022; Oyehan et al., 2023; Akhtar and Maktedar, 2023). An overview of fabrication techniques is shown in Fig. 3.

The top-down method involves the exfoliation of thin layers of MXene films from their MAX phase/non-MAX phase precursors, while the bottom-up method combines different elements to create MXene thin films. The flowchart that shows the various top-down and bottom-up synthesis approaches of MXenes will be useful in providing a general understanding of the various techniques that will be further developed.

A top-down solution synthesis method of  $Nb_2C$  MXene to create fine 2D sheets using hydrofluoric (HF) acid through chemical etching is illustrated in Fig. 4 (Babar et al., 2020a).

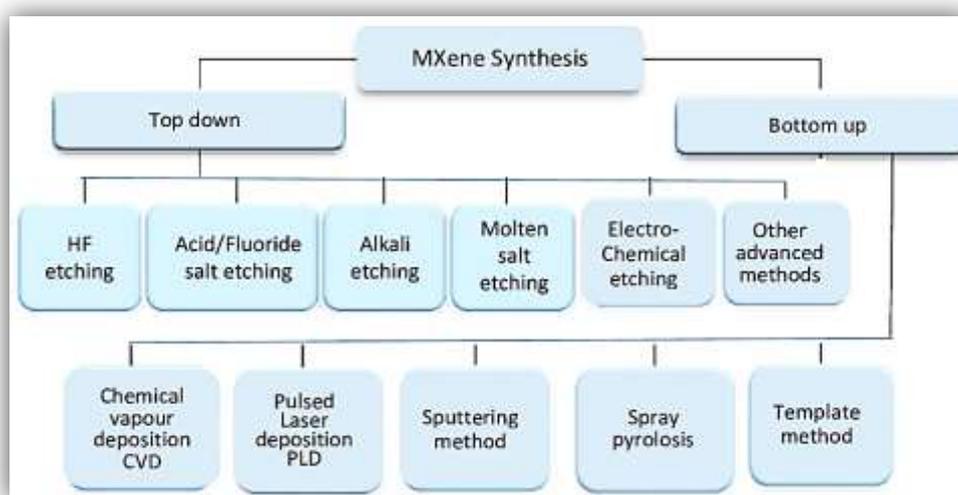


Fig. 3. Flow chart of MXene synthesis techniques.

$M_{n+1}X_nT_x$  ( $n = 1, 2,$  and  $3$ ) is the generic formula for MXenes, where  $M$  is a transition metal (such as Ti, Mo, Cr, Nb, and V),  $X$  is nitrogen or carbon, and  $T_x$  is a variety of surface functional groups (such as  $-OH$ ,  $-O$ , and  $-F$ ). The chemical interacts with acids during the etching process, and it forms the functional groups. Hexagonal crystal cells are layered to create MXenes. Wherever the  $M$  atoms are arranged hexagonally, the  $X$  atoms occupy the octahedral interstitial spaces. (Jiang et al., 2020).

Approximately thirty stoichiometric MXene family representatives have been produced experimentally in the ten years since their discovery, and more than 100 are theoretically predicted. Furthermore, reports of over 20 solid solutions and high-entropy MXenes have been made (Pogorielov et al., 2021).

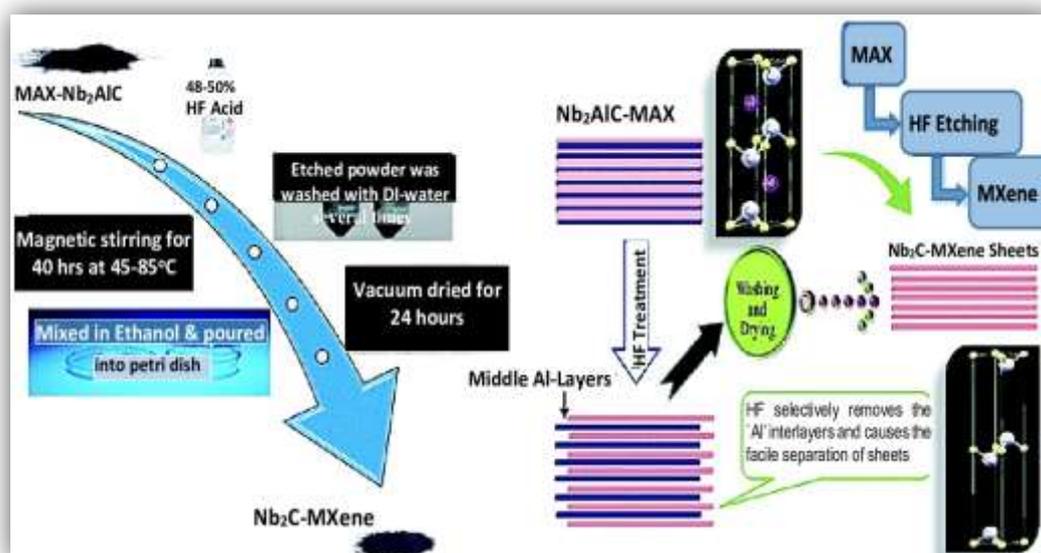
The Al planes from the MAX phases were selectively etched to produce the majority of MXenes (25 out of 30). Thus far, only  $Ti_3SiC_2$ , a non-Al containing MAX phase, has been effectively etched into MXene. Notably, MXenes can also be produced from precursors of non-MAX phases; for example,  $Mo_2CT_z$  was produced by etching Ga layers from  $Mo_2Go_2C$ ,  $Zr_2C_2T_z$  was produced by etching  $Al_3C_3$  layers from  $Zr_3Al_3C_5$ , and  $Hf_3C_2T_z$  was produced by

etching  $(Al,Si)_4C_4$  layers from  $Hf_3(Al,Si)_4C_6$  (Champagne and Charlier, 2021).

Although hydrofluoric acid (HF) treatment is still the most widely used production process, it is hazardous and often requires a delamination step in order to separate the MXene sheets by the intercalation of metallic cations or organic molecules. Consequently several alternatives have been used, namely electrochemical etching,  $NH_4HF_2$ , and in situ HF production through the combination of HCl and LiF solutions. For more details see Champagne and Charlier (2021).

### Structure and properties of MXenes

MXenes are produced in the MAX phase of the precursor material by selectively etching Group A elements. Etching can be used to remove the more chemically reactive Group A elements while maintaining the layered structure of  $M_{n+1}X_n$  because the MX bonds are stronger than the MA bonds. As was previously mentioned,  $T_x$  stands for a variety of surface functional groups, including  $-OH$ ,  $-O$ , and  $-F$ , in the formula for MXenes  $M_{n+1}X_nT_x$ . Wherever the  $X$  atoms occupy the octahedral interstitial sites, the  $M$  atoms are grouped hexagonally (Ampong et al., 2023).



**Fig. 4.** The etching technique and synthesis schematics for the production of 2D MXene. Slightly modified from the original. Reproduced from Babar et al. (2020b) with permission. Copyright the Royal Society of Chemistry.

Extensive computational simulation studies are employed to comprehend the structures of MXenes and identify novel potentially stable compounds. This in reality aids experimental developments. These studies have yielded six distinct forms, namely  $\text{Mo}_2\text{TiC}_2$  and  $\text{Mo}_2\text{Ti}_2\text{C}_3$ , and mono-M elements  $\text{Ti}_2\text{C}$  and  $\text{Nb}_4\text{C}_3$  and ordered in-plane double-M elements such as  $(\text{Mo}_{2/3})_x$ , in which discrete M elements are placed in the basal plane. The vacancies might be randomly dispersed, as in  $\text{Nb}_{1.33}\text{CT}_x$ , or ordered, as in  $\text{Mo}_{1.33}\text{CT}_x$  and  $\text{W}_{1.33}\text{CT}_x$ . These investigations support the search for new and stable MXene compounds and provide insights about the structural characteristics of MXenes (Akhter et al., 2023).

Numerous theoretical and experimental investigations have been conducted to learn more about the chemical and physical characteristics of MXenes since their discovery in 2011. High thermal and electrical conductivities, a variable electronic band gap, different magnetic ordering, and a high Young's modulus are among the special qualities of MXene (Champagne and Charlier, 2021).

The first member of the MXene family,  $\text{Ti}_3\text{C}_2$ , has been the subject of most research because of its wide range of applications. These are energy storage, sensors, photocatalysis, purification of water, electrodes (including flexible electronics), tribology, biomedicine, and SERS (Surface-Enhanced Raman Spectroscopy) substrates. Its exceptional hydrophilic nature, active surface area, and electrical and optical qualities make it stand out among other MXenes representatives, such as  $\text{Nb}_2\text{C}$ ,  $\text{Mo}_2\text{C}$ ,  $\text{Ta}_4\text{C}_3$ ,  $\text{Mo}_2\text{TiC}_2$ , etc. over the past five years, have been actively investigated for a variety of applications (Pogorielov et al., 2021).

Zhu et al. (2021) observed that MXene's ability to control material properties make it more appealing than Graphene. This can be accomplished through processing, doping, and functionalization, while Graphene permits only functionalization.

According to DFT simulations bandgap of MXenes can be tailored by changing the surface terminations. The OH or F terminated MXenes,  $\text{Ti}_3\text{C}_2$  in this example, behave as semiconductors with bandgap values of 0.05 eV and 0.1 eV, respectively, while the non-terminated (Pristine) MXenes behave as metallic conductors in nature. By changing their bandgap, these materials can therefore be used in applications ranging from semiconductors to field-effect transistors (Salim et al., 2019).

Babar et al. (2020b) reported that superconductivity was first observed in as-prepared powdered  $\text{Nb}_2\text{C}$ , with the MXene family having the highest onset transition temperature ( $T_{c,\text{onset}} = 12.5$  K). Spin-polarized generalized gradient approximation (sp-GGA) was used in Wein2K to perform a first principles calculation of density functional theory (DFT) in order to investigate the magnetic nature. The compound's magnetic moment is calculated to be -0.00485; this value is significant despite being small because it indicates the presence of diamagnetism in  $\text{Nb}_2\text{C}$  as it is negative. Because the sample was powdered, it was impossible to measure its transport properties. The work is a major step forward in the study of superconductivity and magnetism in 2D MXene, and it may be investigated further in the future to measure the transport properties.

## **Breakthrough applications and future prospects of MXenes**

### **a. Recent trends of applications of MXenes**

MXenes have hydrophilic surfaces, biocompatibility, reversible surface redox reaction capacity, high electronic conductivity (up to 20,000 S/cm), and visible and infrared optical absorption bands. As a result, the MXenes materials have been investigated for applications in optoelectronics, communication, electrocatalysis, water and gas purification, electrical energy storage, electromagnetic interference (EMI)

shielding, flexible electronics, sensors, catalysis, additive manufacturing, biomedical and healthcare fields, etc.

The special issue *MXenes: From Discovery to Applications* (Xu and Gogotsi, 2020) features an editorial and articles that highlight the latest developments in the field of MXenes, extending their applications beyond energy and catalysis to include the biomedical sciences, optics, and other fields. Naguib et al. (2021) offer a synopsis of the first ten years of MXene research history as well as an outlook on their synthesis and future advancement.

Pogorielov et al. (2021) have reported that a variety of fields, including environmental pollution removal, water desalination, energy storage and harvesting, quantum, sensors, electrodes, and optical devices, have seen a rise in the use of MXene applications recently. Additionally, they have concentrated on the three most significant medical applications: antibacterial therapy, diagnostics, and photothermal cancer therapy. The initial findings regarding the acquisition and examination of high-entropy MXene structures.

EMI (Electromagnetic Interference) shielding is one of the MXenes application sectors that is expanding fast (Iqbal et al., 2020). It is truly dominated by MXenes these days with record performances of  $Ti_3C_2T_x$ . In biomedical applications, MXenes' flexibility and transparency enable their use in the engineering of tunable intraocular lenses. The spin-coating of  $Ti_3C_2T_x$  over a hydrophobic acrylate intraocular lens has been reported by Ward et al. (2020). This leads to a decreased sheet resistance with visible region transmission. MXene's potential in optics is demonstrated by the MXenes coated lens, which showed no biotoxicity towards epithelial cells or release of inflammatory cytokines, suggesting that cataract sufferers may have enhanced eyesight.

We show below in Table 2 the investigated applications and properties of MXenes since 2011 till date. First ten rows of the second column of the table show the year in which the first papers had been reported on each application (Gogotsi and Anasori, 2019). Second column of the next seven rows show the year of recent development and applications of MXene-based films (MFs) (Iqbal et al., 2022). Energy storage was the first area in which MXenes was investigated. It makes up a sizable amount of MXene's operations. Since its introduction into the biomedical area in 2017, the use of MXenes has grown to become one of the most popular study subjects in the domains of theranostics, biosensors, dialysis, photothermal therapy of cancer, and neural electrodes. In areas like electromagnetic applications - such as printed antennas and electromagnetic interference shielding - MXene research is also taking over from other nanomaterials (Gogotsi and Anasori, 2019). They observed that the majority of published works are theoretical, and many predicted properties, like ferromagnetism or topological insulators, have not yet been experimentally validated. There are also very few experimental articles in other disciplines, like electrical and structural applications.

The widespread application of several promising electrochemical processes, such as  $CO_2$  reduction reaction ( $CO_2RR$ ), nitrogen reduction reaction (NRR), oxygen evolution reaction (OER), hydrogen evolution reaction (HER), and oxygen reduction reaction (ORR), is contingent upon the utilization of capable electrocatalysts. A surface-sensitive method known as surface-enhanced Raman spectroscopy (SERS) or surface-enhanced Raman scattering (SERS) increases Raman scattering by molecules adsorbed on abrasive metal surfaces or by nanostructure. Photocatalysis is a potential, currently among the most important topics for addressing environmental and energy problems (Sun et al., 2022).

**b. Some breakthrough applications**

We now discuss and provide some breakthrough and diverse applications of the wonder material MXenes below. Both current and future prospects will also be mentioned.

**(i) Electrochemical energy storage**

MXenes are efficient electrochemical energy storage materials and have thus shown a prominent role as electrodes in rechargeable Li-

and Na-ion batteries, Li-S batteries and supercapacitors and ionic batteries. MXenes are characterized by a large specific surface area, a high number of active sites, a variety of surface functional groups, and an adjustable interlayer distance. The photocatalytic fuel production, such as hydrogen evolution from water splitting, and CO<sub>2</sub> reduction have exciting potential in terms of energy conversion (Pang et al., 2019).

**Table 2. Explored applications of MXenes since 2011 till date.**

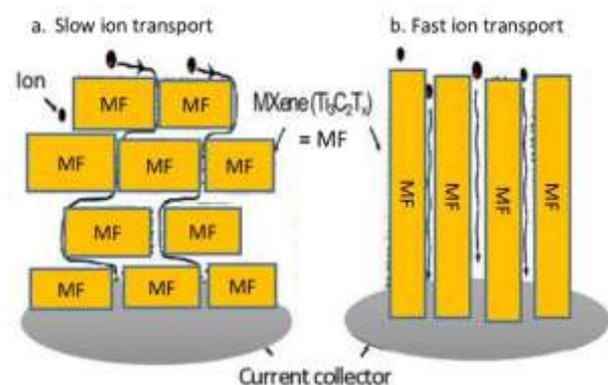
MXenes	Year	Explored applications
Ti <sub>3</sub> C <sub>3</sub> T <sub>x</sub>	2011	Synthesis, Stability, Intercalation, Other Processing.
Ti <sub>3</sub> C <sub>3</sub> T <sub>x</sub>	2012	Energy: Electrochemical Capacitors, Micro-supercapacitors. Bateries: Li-ion, Na-Ion, Mg-Ion, Li-Sulfur. Energy Harvesting, Textile, Flexible energy storage.
Ti <sub>3</sub> C <sub>3</sub> T <sub>x</sub> +other MXenes	2012	Structural: Mechanical, Composites.
Other MXenes	2013	Electronics: Electrical, Thermal, High Electrical Conductivity, Topological Insulators, Magnetic.
Ti <sub>3</sub> C <sub>3</sub> T <sub>x</sub>	2015	Environment: Clean Air, Clean Water, Membrane.
Other MXenes	2015	Optical: SERS, Laser, Photo Detectors.
Ti <sub>3</sub> C <sub>3</sub> T <sub>x</sub>	2016	Electromagnetic: EMI Shielding, Antenna, Microwave Absorption.
Other MXenes	2016	Catalysis: HER, OER, NRR, CO <sub>2</sub> RR.
Ti <sub>3</sub> C <sub>3</sub> T <sub>x</sub>	2017	Sensors: Gas, Humidity, Strain.
Ti <sub>3</sub> C <sub>3</sub> T <sub>x</sub>	2017	Biomedical: Cancer Treatment, Dialysis Disorder, Neural Electrodes.
MXene-based films (MFs)	2016	Spray coating and Laser cutting.
	2017	Electrospinning, Spray coating, Vacuum filtration.
	2018	Stamping, Mechanical cutting, Screen printing.
	2019	3D printing, Inkjet printing, Electrochemical process.
	2020	Ion-beam cutting.
	2021	Vacuum filtration, Laser cutting fabrication, Screen printing.
	2022	Templating and Injection, Vacuum filtration.

### (ii) MXene: A breakthrough for fast battery charging

Maintaining the energy density and power density (the pace at which the device can charge) of a charge-storing material involves making sure that ion channels stay clear. The Drexel team propped the MXene flakes in the electrodes vertically to avoid the stacking problem, which prevents ion diffusion. In this design, MXene is able to create additional pathways for ions to travel through the material quickly, in contrast to Traditional Battery (Adapted from Xia et al., 2018). A Model drawing of ion transport in such system using  $Ti_3C_2T_x$  MXene films (MF) is shown in Fig. 5.

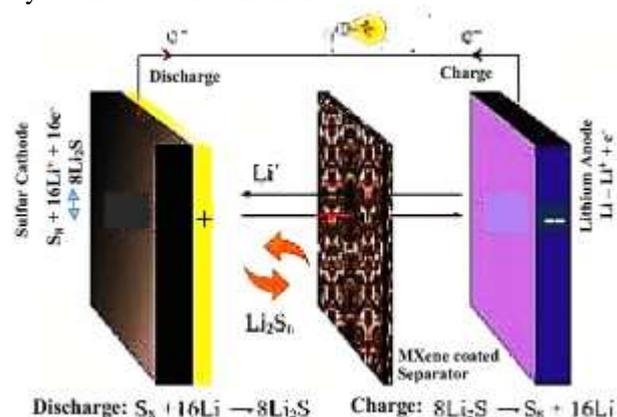
### (iii) Emerging battery beyond Li-ion battery

In recent years, there has been a huge increase in research into next-generation battery technology beyond Li-ion batteries, or LIBs. The lack of suitable electrode materials has been a major obstacle that has significantly limited their development. Due to their many beneficial properties, MXenes are in demand as electrode materials for these emerging batteries (Ming et al., 2021). The electrolyte, or polyethylene oxide, has better ionic conductivity when  $Nb_2CT_x$  MXene is added. By incorporating  $Nb_2CT_x$  MXene, the ionic conductivity of the electrolyte (PEO, polyethylene oxide) is improved. Additionally, the nanosheets efficiently adsorb polysulfides on forming Nb-S bonds which inhibits the shuttle effect of polysulfides within the PEO framework.



**Fig. 5.** Ion transport in  $Ti_3C_2T_x$  MXene films stacked horizontally and vertically, respectively (a, b). The pathways for ion transport are shown by the vertically curved lines.

PEO is compatible with Li-S batteries, has strong lithium salt dissociation capability, and is well processable. Natural abundant sulfur with high capacity, and high specific energy density of lithium-sulfur (Li-S) batteries make them one of the most desirable candidates for next generation energy storage systems ( $1675 \text{ mAhg}^{-1}$  and  $2600 \text{ Whkg}^{-1}$ , respectively) (Huang et al., 2022). Lithium-sulfur batteries with up to 1,500 charge and discharge cycles have been demonstrated.



**Fig. 6.** Design of the Li-S cells using MXene PP separator (Adapted from Song et al., 2016).

Lithium-sulfur (Li-S) batteries are considered to be among the most promising options to overcome the specific energy constraints of commercial lithium-ion batteries due to their low cost, high theoretical specific energy, and environmental credentials.

With a minimal mass loading of  $0.1 \text{ mg cm}^{-2}$  and a thickness of just 522 nm, the  $Ti_3C_2T_x$  MXene can create a homogeneous coating layer in favor of the ultrathin 2D structure. The lithium-sulfur batteries with MXene-functionalized separators (Fig. 6) operate better than other lithium-sulfur batteries, exhibiting high specific capacities and cycling stability, due to their enhanced electric conductivity and efficient polysulfide trapping (Song et al., 2016).

### ■ Promising results and future applications

**Laser modified Leap:** In order to improve MXene's electrode characteristics, researchers from KAUST, KSA, recently employed laser pulses. This could result in a breakthrough in rechargeable battery technology that could outperform conventional lithium-ion batteries (Bayhan et al.,

2023). A lithium-ion battery was used to evaluate an anode made from this laser-scribed material through a total of 1000 charge-discharge cycles. Surprisingly, the material demonstrated a four-fold increase in electrical storage capacity with the nanodots compared to the unaltered MXene, almost matching the theoretical peak capacity of graphite. Furthermore, during the testing phase, laser modified material maintained its maximum potential. The promise of MXene-based hybrid materials for high-performance energy storage applications has thus been highlighted by the laser-induced synthesis method.

An anode composed of this laser-scribed material was tested through a total of 1000 charge-discharge cycles using a lithium-ion battery. Remarkably, as compared to the unaltered (Pristine) MXene, the material showed a four-fold increase in electrical storage capacity with the nanodots. Moreover, during the testing phase, the material changed by laser maintained its maximum potential. Thus, laser-induced synthesis technique highlights the potential of MXene-based hybrid materials for high-performance energy storage applications.

#### (iv) MXenes as electrocatalysts for HER

Hydrogen has drawn a lot of attention because of the global issues of environmental degradation and energy scarcity. Numerous benefits of hydrogen include its high energy density, low emissions of pollutants or greenhouse gases, recycling potential, and more. There are several ways to create hydrogen, such as burning biomass or fossil fuels, fermenting marsh gas, or using organic waste. Among which, the hydrogen evolution reaction (HER) based on water splitting has proven to be a cost-effective and ecologically sustainable method.

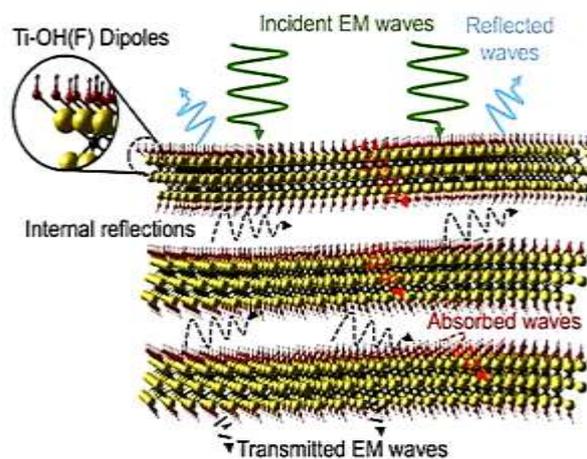
In order to obtain hydrogen in HER, the electrocatalyst is important. Electrocatalysts based on precious metals, including Pt and Ru, show efficiency and stability in this regard. However, a lack of resources and growing costs have made it difficult to meet the growing demand for electrocatalysts based on precious metals. In

addition there are some problems of electrocatalysis in the existing methods.

With the advances of materials, MXenes show the ability to solve the issues listed above. MXenes have been considered a class of promising HER electrocatalysts due to their intrinsic layered structure and high carrier mobility (Bai et al., 2021).

#### (v) MXene: Best-ever protection against EM interference

Electromagnetic interference shielding is one of the MXenes application domains that is expanding fast. These days, MXenes really dominate it with record performances of  $Ti_3C_2T_x$  and  $Ti_3CNT_x$ . Recent progress of the MXene family which entered the field in 2016 for protection against electromagnetic jamming, including EMI shielding and microwave absorption is noteworthy.



**Fig. 7. EMI shielding mechanism of MXene-SA composite films. Reproduced with permission from Shahzad et al.(2016). Copyright 2016, the American Association for the Advancement of Science.**

MXenes may contain “electromagnetic pollution” such as buzzing sound/EM. Radio noise can come from anything that generates, transmits, or uses electrical power, including televisions, Internet cables, cell phones, tablets, and laptops. Figure 7 shows that MXene protects against electromagnetic interference by absorbing and trapping waves between its layers (Shahzad et al., 2016). MXene works by both reflecting and absorbing electromagnetic fields. Waves. Some bounce of the

coating surface immediately. Others pass through but lose energy in atomically thin layers of material. Lower energy EM waves are reflected by the inner layers until they are completely absorbed.

Remarkable advancements in communication technology coincide with the introduction of 5G technology. Compared to 4G cellular networks, it offers improved data-carrying capacities and transfer speeds that are about 100 times faster. Due to the wide frequency range of electromagnetic waves (EMWs) that these systems generate, receive, and/or transmit, EMI is prone to intensify, impairing device performance and jeopardizing system security (Iqbal et al., 2021). This review demonstrates how MXenes' inherent qualities such as their excellent metallic conductivity, 2D sheet morphology, tunable surface chemistry, light weight, and ease of solution processing offer them a promising future for EMI shielding applications.  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene sheets with thicknesses in the nanometer to submicron range showed the best shielding efficiency. Through external modifications such as metastructure formation,  $\text{Ti}_3\text{CNT}_x$  MXene films demonstrated industry-leading shielding performance, superior to highly conductive  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene films and metallic films of comparable thickness.

#### (vi) Spintronic devices - 2D information superhighway

Spintronics is one of the emerging areas where next-generation nanoelectronic devices can reduce power consumption and increase storage and processing capabilities. MXenes or other nanomaterial-based devices exploit the spin degrees of freedom of electrons and/or holes, which can also interact with their orbital moments.

The ability to dynamically alter the spin of an electron presents opportunities for the development of new quantum-mechanical devices, including spin valves, spin transistors, and high-density memory. Particularly interesting are spintronic devices in the fields of quantum data processing, computing, and sensing.

#### (vii) MXenes in Nanogenerators

A device that transforms mechanical energy into electrical energy at the nanoscale is called a

nanogenerator. Piezoelectric and triboelectric effects are the two underlying principles of nanogenerator operation. MXenes are frequently used to create effective nanogenerators in combination with other active materials. Both piezoelectric and triboelectric energy harvesting applications can make use of these nanocomposites. According to reports, a blue energy solution that transforms mechanical energy into electrical power is the piezoelectric nanogenerator (PENG).

#### ■ Piezoelectric Nanogenerators (PENGs)

The applied mechanical stress causes a displacement of the positive and negative charge centers within the material's crystal structure, resulting in the piezoelectric effect at the microscopic level. An electric potential, or voltage, is created across the material as a result of this displacement, which also causes electric polarization.

According to the most recent studies, Pt-infiltrated MXene on a paper substrate serves as a starting of the development of the flexible piezoresistive sensor. The sensitivity has increased from  $0.08$  to  $0.5 \text{ kPa}^{-1}$ , the detection limit has been extended from  $5$  to  $9 \text{ kPa}$ , the response time has decreased from  $200 \text{ ms}$  to  $20 \text{ ms}$ , and the recovery time has decreased from  $230 \text{ ms}$  to  $50 \text{ ms}$  (Qi et al., 2023).

Due to their low cost of fabrication, simple signal collection, and numerous useful applications-including smart displays, skin-inspired electronics, and portable healthcare monitors - these sensors have attracted a lot of attention.



**Fig. 8. MXene-based TENG mounted on different parts of the body for harvesting energy from human muscle movements and from feet pressure.**

### ▪ **Triboelectric Nanogenerators (TENG)**

TENGs generate electricity from friction. When two dissimilar materials come into contact and then separate, charge transfer occurs due to the triboelectric effect.

MXenes are helpful as constituents of TENG, which converts mechanical motion into electrical power. According to research, wearable technology, computers, mobile phones, and portable gadgets may all eventually be powered by these cutting-edge materials.

The ability to power electronic devices utilizing waste mechanical energy from the environment has been made possible by the quick development of energy harvesting employing nanogenerators. The development of TENG has advanced to the point of large-scale, scalable manufacture, and it is beginning to get commercialized.

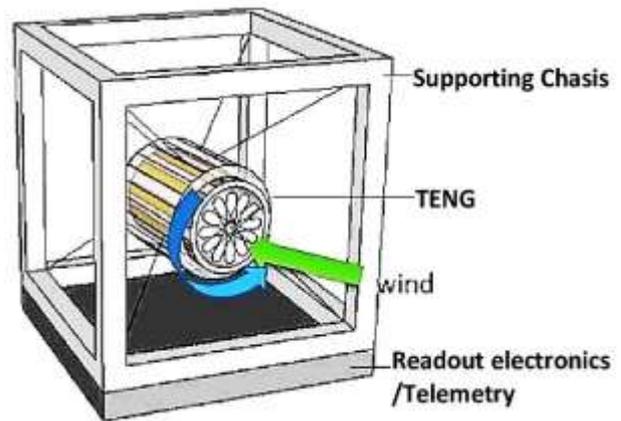
The integration of wearable technology in clinical settings shows promise in enhancing diagnosis, enabling real-time monitoring of disease progression, and tailoring treatment to individuals.

In recent years, researchers have focused on harnessing environmental energy to generate electricity, addressing the need for a cleaner and more sustainable power supply (Jeewandara, 2019). The conversion of mechanical energy from the environment offers a green approach that is crucial in the development of wearable electronics and sensor networks for the Internet of Things (IoT).

### ▪ **TENG for Mars exploration**

This project is to field-test the in-house developed TENG that can harvest energy from the wind and all kinds of vibrations and motions. By rubbing two sheets of material together, the triboelectric effect and electrostatic induction combine to transform mechanical energy from the environment - such as wind and other motion or vibration - into electrical energy. This device is known as a harvesting device for energy. Because of its advantages in terms of

launching and propulsion costs, this is an incredibly lightweight substitute for traditional electromagnetic motors, which are heavy. NASA states that this makes it a perfect fit for Mars exploration.



**Fig. 9. Developed TENG for Mars exploration.**

One day, using TENG for wind power generation on Mars will require overcoming a number of known and unknown technical obstacles. The next step in the process is to create a functional test bed in a balloon flight (Meyyappan and Kang, NASA).

### (viii) **Printed structures**

Due to the hydrophilicity and extremely negative charge of MXene flakes, which have a zeta potential of about -30 mV, MXene can be uniformly dispersed in water, which has led to a rapid increase in the number of printed electronic products based on MXene. These properties of MXene also contribute to the process of producing colloidal particle dispersions in a variety of organic and aqueous solvents. (Ahmed et al., 2022).

Furthermore, recent advances in the field of MXene inks have led to promising results in the development of additive-free devices. This process is considered an innovative strategy due to its environmental impact, especially when compared to previous printing techniques that used additives.

### ▪ **Wearable sensors in smart fabrics**

Wearable sensors can be described as smart electronic devices that are worn on the body as an

accessory or part of a garment. Sensors embedded in wearable devices can be used to continuously monitor physiological and motion variables.

In addition to data transmission, textile sensors in the form of a computer device worn on the body can also be used as intelligent sensor technology for accessing the mobile Internet. The next generation of human-machine interfaces can be built on these sensors. One of the main drivers of the development of textile sensors is the continuous discovery of new conductive materials. Recently a 2D MXene material that performs exceptionally well has drawn a lot of attention because of its strong conductivity, processability, and mechanical stability (Jin and Bai., 2022).

### c. Versatile biomedical and related applications

MXenes represent a fascinating frontier in biomedical research, bridging the gap between nanotechnology and healthcare. Their multifaceted properties make them suitable for drug delivery, phototherapy, diagnostic imaging, biosensing, antimicrobial, biosafety evaluations and tissue engineering (Lin et al., 2018; Lu et al., 2021; Garg and Vitale, 2023; Lee et al., 2024).

<b>MXenes</b>	<b>Electrophysiology</b>	Wearable electronics, Implantable electrodes, Photothermal stimulation
	<b>Biosensing</b>	<b>Electrochemical:</b> Fluorescent imaging <b>Diagnostic imaging:</b> DNA sensing, Viral sensing
	<b>Antimicrobial</b>	<b>Antimicrobial:</b> Antiviral
	<b>Therapeutics</b>	<b>PIT &amp; PDT; Drug &amp; gene delivery:</b> Wound healing <b>Synergistic therapy:</b> Intracocular lenses, Dialysis
	<b>Tissue engineering</b>	Stem cell engineering, Regenerative medicine, Artificial organs, Immunomodulation

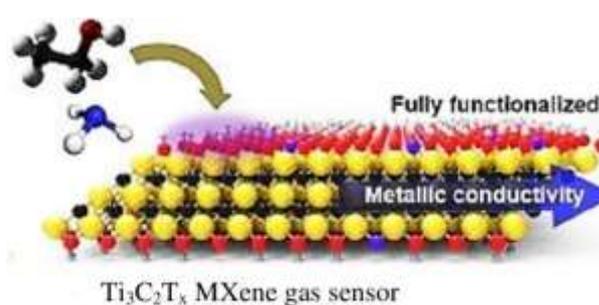
**Table 10. Emerging and novel areas of applications of MXenes e.g., in bioelectronics, tissue engineering, immunotherapy, therapeutics.**

#### (i) MXene as sensitive gas sensor

The human body is a chemical metabolism factory, dogs are able to detect volatile organic compounds

(VOCs) that are expelled by humans. The presence of certain compounds or the distinct chemical signatures of these VOCs can offer crucial hints about our health.

When a gas interacts with the MXene surface, it leads to changes in electrical conductivity. These conductivity variations are correlated with gas concentration, enabling sensitive detection. MXenes can form composite materials with other nanomaterials, enhancing their gas sensing capabilities. Composite structures increase surface area, interlayer spacing, and active sites for gas adsorption. MXenes are used for detecting various gases, including: Volatile Organic Compounds (VOCs): Such as acetone, ethanol, and benzene.



**Fig. 11. Ultrahigh signal-to-noise ratio metallic  $Ti_3C_2T_x$  MXene gas sensors. Reproduced with permission from Kim et al. (2018). Copyright © 2018 American Chemical Society.**

Solid-state gas sensors that achieve great sensitivity may be able to precisely identify chemical substances. Specifically, early illness diagnosis depends on the detection of VOCs at the parts per billion (ppb) level. Two conditions must be met at the same time in order to achieve great sensitivity: Existing sensor materials are unable to fulfill (i) low electrical noise and (ii) strong signal requirements. Existing sensor materials are unable to fulfill these two requirements (Kim et al., 2018).

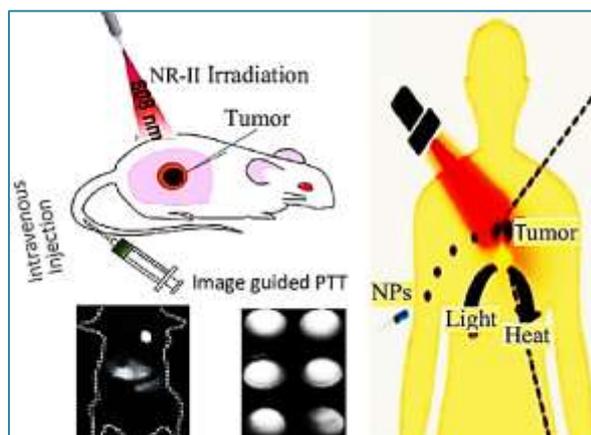
Gas sensors must be able to precisely identify acetone molecules in breath at concentrations of between 300 and 1,800 parts per billion in order to identify diabetes. Gas sensors need to identify

ammonia molecules in breath at 50–200 parts per billion in order to identify peptic ulcers. MXenes are an ideal gas sensor due to their great sensitivity and low noise, as demonstrated by theoretical work that has been verified by expt. These unique properties make  $Ti_3C_2T_x$  superior gas-sensor over previously studied materials. Their versatility, stability, and sensitivity contribute to the development of advanced sensors for environmental monitoring, safety, and health (Kim et al., 2018).

### (ii) Targeted delivery of anticancer drugs or Nanomaterials

A cancer treatment called photothermal therapy (PTT) uses heat produced in tumor tissue that is exposed to near-infrared (NIR-II, 1000–1350 nm) light to cause the death of cancer cells. Utilizing NIR absorbents helps to produce heat more effectively. MXenes are great candidates for PTT because of their high absorbance in the near- infrared-II (NIR-II) region (An et al., 2021; Wu et al., 2023).

Nomura et al. (2020) has shown that PTT is an extremely dependable cancer treatment when it combines thermal dosimetry with an NIR absorbent.



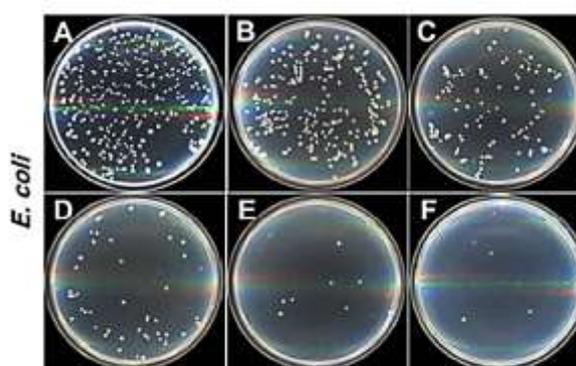
**Fig. 12. PTT and NIR-II/MR imaging of cancer/tumor using the MXene nanocomposites (collected from several sources and modified).**

### (iii) Antibacterial activity of $Ti_3C_2T_x$ MXene

In a colloidal solution, the antibacterial qualities of monolayer and multilayer  $Ti_3C_2T_x$  MXene flakes were examined (Rasool et al., 2016). Initially,

they proposed MXene's antimicrobial mechanism as a 'nanoknife'.  $Ti_3C_2T_x$  demonstrates stronger antibacterial activity against Gram-negative *E. coli* and Gram-positive *B. subtilis* than graphene oxide, which is widely reported as an antibacterial agent.

Fig. 13 illustrates the observed conc-dependent antibacterial activity. Photographs of agar plates onto which *E. coli* bacterial cells were recultivated after treatment for 4 h with 0  $\mu\text{g/mL}$  (A), 10  $\mu\text{g/mL}$  (B), 20  $\mu\text{g/mL}$  (C), 50  $\mu\text{g/mL}$  (D), 100  $\mu\text{g/mL}$  (E), and 200  $\mu\text{g/mL}$  (F) of  $Ti_3C_2T_x$ , respectively. Bacterial suspensions in deionized water without  $Ti_3C_2T_x$  MXene material were used as control (Rasool et al., 2016).



**Fig. 13. Concentration dependent antibacterial activities of the  $Ti_3C_2T_x$  in aqueous suspensions. Reproduced with permission from Rasool et al. (2016). Copyright © 2018 American Chemical Society.**

In addition to having strong antibacterial, anti-inflammatory, and cell proliferation and migration-promoting qualities, MXene-based dressings also somewhat enhance their mechanical or physico-chemical qualities (Li et al., 2024). MXenes are now being developed and used in a variety of wound dressings, including hydrogels, films, scaffolds, and sponges.

The excellent antibacterial, anti-inflammatory, and antioxidant properties of MXenes materials have been demonstrated in several recent studies. This has greatly aided in the development of MXenes in the fields of tissue engineering and skin regeneration. The development of novel wound dressings has advanced considerably as a result of several recent studies on the addition of MXenes.

#### **(iv) Self-powered cardiovascular electronic devices (CED)**

Cardiovascular disease is a leading cause of death worldwide. Current therapeutic approaches (such as drugs, cell-based therapy, and heart transplantation) have limitations in terms of efficacy and practical availability. MXenes play a crucial role to the development of self-powered CEDs. They are perfect for mediator-free biosensors because they allow direct electron flow between bioreceptors and electrodes. Additionally, MXenes act as frameworks for the immobilization of biomolecules, maintaining the activity of proteins.

Millions of patients with cardiovascular disease now experience lower rates of morbidity and death thanks to the development of wearable or implantable electronic devices, which have completely changed cardiovascular medicine's diagnostic and therapeutic approaches. This kind of self-powered technology produces electricity by converting energy from the environment or the human body. It can be used as a sustainable power source to augment or replace battery technology.

By providing continuous health monitoring both inside and outside of the clinical setting, wearable or portable CEDs have completely changed digital and mobile health monitoring. Wearable electronics have a plethora of potential uses in cardiovascular care, including monitoring vital signs and aiding in the diagnosis of both acute and chronic cardiovascular illness. Based on their functions, wearable cardiac electrodes can be categorized into four primary groups: heart rate monitors, hemodynamic monitors, daily activity monitors, and electrocardiography and heart rhythm monitors. Wearable electronics for cardiovascular health are available in a variety of styles, such as T-shirts, vests, smart watches, rings, wrist bands (cuffs), and chest patches (Amani et al., 2024).

#### **Futuristic look**

Even though MXene applications have advanced greatly, a few difficult problems still need to be fixed before new MXene-based products are released into the market. The first technological issue is from the manufacture of MXene using largely acidic chemicals including fluorine, which are hazardous to the biological environment. This problem might be partially resolved by bottom-up synthesis, but it requires technological advancement and scaling up. There have only been preliminary efforts made in this regard. If efficient delamination of salt-etched MXenes can be accomplished, molten salt etching holds great potential. MXene's cost has dropped dramatically in recent years, although it is still costly, primarily due to the materials' continued scarcity for large-scale manufacturing.

MXenes might oxidize while being stored. This could have a substantial impact on their characteristics, leading to further deterioration under specific application circumstances. MXenes, on the other hand, are stable for months in suspension and for many years in dry films due to enhanced stoichiometry and flake perfection. The synthesis and post-production processes of MXene have significantly improved in recent years due to the application of new technologies and solutions, which have dramatically improved the compound's characteristics and opened up new application opportunities (Pogorielov et al., 2021).

In the field of energy storage, MXenes show promise, and research is still being done to fully realize their potential. This fascinating topic is still being shaped by viewpoints and challenges for the future.

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