DOI: 10.36297/vw.jei.v8i2.406

VW Engineering International, Volume: 8, Issue: 2, 20-41

MXene-Based Nanomaterials for Next-Generation Energy Storage and Flexible Electronics

Aarav Sharma[1*], Nidhi Verma[2*], Rahul Sen[3*]

[1]Department of Materials Engineering, NIT Raipur,Chhattisgarh, India
[2]Department of Nanoscience and Technology, Indian Institute of Information Technology Design and Manufacturing, Kancheepuram, India
[3]Department of Electrical Engineering, NIT Srinagar, Srinagar, India
[*]Email: aarav.me@nitrai.ac.in, nidhiverma@iiftdm.edu, rahul.ee@nitsgr.ac.in

Received: Feb 10, 2026
Accepted: Jun 13, 2026
Published online: Jun 15, 2026

Abstract: The increasing demand for efficient energy storage technologies and flexible electronic devices has stimulated extensive research into advanced nanomaterials capable of simultaneously delivering high electrochemical performance and mechanical adaptability. MXenes, a rapidly emerging family of two-dimensional transition metal carbides, nitrides, and carbonitrides, have demonstrated exceptional potential in these applications owing to their metallic conductivity, hydrophilic surfaces, tunable chemistry, and layered structures. Among the various MXene compositions reported to date, $Ti_3C_2T_x$ has received considerable attention due to its ease of synthesis and outstanding electrochemical properties. This study explores the application of MXene-based nanomaterials in next-generation energy storage systems and flexible electronic devices. Particular emphasis is placed on understanding the relationship between MXene structure, surface functionalization, and performance characteristics relevant to supercapacitors, rechargeable batteries, flexible sensors, and wearable technologies. Current advances in synthesis techniques, composite engineering strategies, and device fabrication methodologies are critically discussed. Furthermore, the challenges associated with oxidation stability, sheet restacking, and scalable manufacturing are examined in detail. The findings indicate that MXene nanomaterials possess substantial potential to revolutionize sustainable energy storage technologies and enable the development of mechanically robust electronic systems. Continued efforts directed toward environmentally responsible synthesis routes, interfacial engineering, and multifunctional material design may accelerate the translation of MXene research from laboratory investigations to industrial applications.

Keywords: MXenes, $Ti_3C_2T_x$, Nanotechnology, Supercapacitors, Flexible Electronics, Energy Storage

1. Introduction

The global transition toward renewable energy systems, portable electronics, and intelligent wearable technologies has significantly increased the demand for advanced materials capable of addressing the limitations associated with conventional energy storage devices and electronic components. Traditional electrode materials often exhibit inadequate electrical conductivity, low energy density, limited flexibility, and poor long-term stability. Consequently, the development of novel nanomaterials has become a major focus of scientific research in recent years.

Two-dimensional materials have emerged as promising candidates for energy-related applications because of their unique structural and physicochemical characteristics. Following the discovery of graphene, numerous layered nanomaterials have been investigated for applications in electrochemical energy storage, sensing technologies, and electronic systems. Among these materials, MXenes have attracted extraordinary attention due to their exceptional combination of metallic conductivity and solution processability [1].

MXenes constitute a rapidly expanding family of two-dimensional transition metal carbides, nitrides, and carbonitrides represented by the general formula $M_{n+1}X_nT_x$, where M denotes an early transition metal, X

 DOI: 10.36297/vw.jei.v8i2.406

represents carbon and/or nitrogen atoms, and T_x corresponds to surface functional groups generated during synthesis [2]. The first MXene, $Ti_3C_2T_x$, was synthesized through selective chemical etching of Ti_3AlC_2 MAX phases, establishing an entirely new category of functional nanomaterials [3].

One of the distinguishing characteristics of MXenes is their high electrical conductivity, which in some cases approaches values comparable to those of metallic conductors. In addition, the presence of hydrophilic surface terminations facilitates dispersion in aqueous media and promotes favorable interactions with electrolytes [4]. These characteristics make MXenes particularly attractive for electrochemical applications involving rapid ion transport and efficient charge transfer processes.

Energy storage technologies represent one of the most extensively explored application domains for MXene nanomaterials. The increasing deployment of renewable energy sources and electric vehicles necessitates the development of high-performance supercapacitors and rechargeable batteries capable of delivering both high energy density and high power density. Owing to their layered structures and large surface areas, MXenes have demonstrated remarkable electrochemical performance in these systems [5].

Flexible electronics constitute another rapidly growing field benefiting from advances in MXene research. Wearable healthcare devices, smart textiles, electronic skins, and foldable displays require conductive materials capable of maintaining their functionality under repeated mechanical deformation. MXenes exhibit excellent flexibility, enabling their incorporation into diverse sensing platforms and energy storage architectures [6].

Despite these advantages, several challenges continue to impede the practical implementation of MXene technologies. Oxidative degradation during storage, aggregation of nanosheets during electrode fabrication, concerns regarding environmentally hazardous etching reagents, and limitations associated with large-scale production remain critical issues requiring further investigation [7]. Addressing these barriers will be essential for facilitating the commercialization of MXene-enabled devices.

The present study aims to examine the role of MXene-based nanomaterials in next-generation energy storage systems and flexible electronic applications. Particular emphasis is placed on $Ti_3C_2T_x$ MXene due to its widespread investigation and technological relevance. Furthermore, recent advances in synthesis strategies, composite engineering approaches, and device fabrication methodologies are critically analyzed to identify future directions for research and innovation.

2. Literature Review

Since the initial synthesis of $Ti_3C_2T_x$ MXene, the field has experienced remarkable growth, leading to the development of numerous MXene compositions exhibiting diverse physicochemical properties. Extensive investigations have focused on understanding the influence of composition, surface chemistry, and structural modifications on material performance across various engineering applications [2].

Early studies primarily emphasized the synthesis and characterization of MXene nanosheets derived from MAX phases through selective etching processes [3]. Subsequent investigations expanded this knowledge by exploring alternative etching methodologies designed to reduce environmental hazards while preserving desirable structural characteristics [8].

In the context of energy storage, MXene-based supercapacitors have demonstrated outstanding promise due to their ability to facilitate rapid ion transport and pseudocapacitive charge storage mechanisms [5]. The presence of abundant surface functional groups enhances electrochemical activity, while metallic conductivity contributes to efficient electron transport. Several studies have reported substantial improvements in capacitance through the incorporation of conductive polymers, carbon nanotubes, and graphene derivatives into MXene matrices [9].

Rechargeable battery technologies have similarly benefited from advances in MXene engineering. Layered MXene architectures provide favorable environments for lithium-ion and sodium-ion intercalation processes, resulting in enhanced rate capabilities and cycling stability [10]. Surface engineering strategies aimed at regulating interlayer spacing have further contributed to improvements in electrochemical performance.

The emergence of flexible electronics has stimulated investigations into the mechanical properties of MXene-based materials. Flexible pressure sensors fabricated using $Ti_3C_2T_x$ MXene have exhibited high sensitivity, rapid response times, and excellent operational durability under repeated bending conditions [6]. Such characteristics make MXenes particularly suitable for applications involving wearable healthcare monitoring systems and human–machine interfaces.

Electromagnetic interference shielding represents another area in which MXene nanomaterials have demonstrated considerable potential. Their excellent electrical conductivity and layered structures enable efficient attenuation of electromagnetic radiation, thereby contributing to the protection of sensitive electronic systems [11].

Notwithstanding these advances, several challenges remain unresolved. Oxidation-induced degradation significantly affects long-term stability, particularly under ambient conditions. Furthermore, the tendency of MXene nanosheets to restack during processing reduces accessible surface area and limits electrochemical performance [7]. Consequently, ongoing research increasingly emphasizes the development of protective coatings, hybrid nanostructures, and environmentally sustainable synthesis routes capable of overcoming these limitations.

Overall, the available literature underscores the transformative potential of MXene nanomaterials across diverse technological domains. Nevertheless, achieving widespread industrial adoption will require interdisciplinary efforts integrating materials science, electrochemistry, manufacturing engineering, and sustainability considerations.

Table 1. Comparative Properties of Selected Two-Dimensional Nanomaterials

Property	**Graphene**	**MoS_2**	**$Ti_3C_2T_x$ MXene**	**Black Phosphorus**
Electrical Conductivity	Excellent	Moderate	Excellent	Moderate
Hydrophilicity	Poor	Moderate	High	Moderate
Surface Functionalization	Limited	Moderate	Extensive	Limited
Mechanical Flexibility	Excellent	Good	Excellent	Good
Ion Transport Capability	Moderate	Good	Excellent	Moderate
Suitability for Supercapacitors	High	Moderate	Very High	Moderate
Compatibility with Flexible Devices	High	Moderate	Very High	Moderate

Table 2. Engineering Applications of MXene Nanomaterials

Application Area	**Functional Role**	**Engineering Significance**
Supercapacitors	Electrode material	High power density
Lithium-ion Batteries	Conductive host matrix	Enhanced cycling stability
Sodium-ion Batteries	Ion storage framework	Cost-effective alternatives
Flexible Sensors	Conductive sensing element	Wearable healthcare monitoring
Electronic Skin	Stretchable interface	Human–machine interaction

Smart Textiles	Integrated energy component	Portable electronics
Electromagnetic Shielding	Radiation attenuation material	Electronic protection
Flexible Displays	Conductive coating	Foldable device development

Objectives of the Study

The objectives of this investigation are as follows:

- To examine the physicochemical characteristics of $Ti_3C_2T_x$ MXene nanomaterials.
- To evaluate the applicability of MXenes in advanced energy storage technologies.
- To investigate the integration of MXene architectures into flexible electronic systems.
- To identify current limitations restricting large-scale commercialization.
- To propose future research directions for sustainable MXene-based engineering innovations.

3. Synthesis Strategies and Characterization Techniques of MXene Nanomaterials

Synthesis Strategies for MXene Nanomaterials

The synthesis route significantly influences the physicochemical properties, electrochemical performance, and environmental sustainability of MXene nanomaterials. Since the first successful preparation of $Ti_3C_2T_x$ MXene in 2011, numerous methodologies have been developed to optimize yield, reduce structural defects, and minimize environmental hazards associated with conventional etching procedures [12].

MXenes are typically derived from layered MAX phases, which possess the general formula $M_{n+1}AX_n$, where M represents an early transition metal, A denotes an A-group element, and X corresponds to carbon and/or nitrogen atoms. The selective removal of the A-element layer results in the formation of two-dimensional MXene nanosheets [2].

◆ **Hydrofluoric Acid (HF) Etching**

Hydrofluoric acid etching represents the earliest and most widely employed technique for MXene synthesis. Naguib et al.successfully synthesized $Ti_3C_2T_x$ by immersing Ti_3AlC_2 powders in concentrated hydrofluoric acid, thereby selectively removing aluminum layers [3].

The simplified reaction can be represented as:

$$Ti_3AlC_2 + 3HF \rightarrow Ti_3C_2 + AlF_3 + 1.5H_2$$

Although HF etching facilitates efficient exfoliation, several limitations have been identified, including:

* Safety concerns arising from HF toxicity.

* Structural defects induced by aggressive etching conditions.

* Difficulties associated with large-scale implementation.

Consequently, researchers have increasingly explored safer alternatives.

◆ **In-Situ HF Generation**

A more environmentally favorable approach involves generating HF in situ through reactions between fluoride salts and hydrochloric acid. Common fluoride salts include lithium fluoride, sodium fluoride, and potassium fluoride [13].

This method offers several advantages:

- Reduced direct exposure to concentrated HF.
- Improved control over surface functionalization.
- Enhanced interlayer spacing due to cation intercalation.

$Ti_3C_2T_x$ synthesized through LiF–HCl systems often exhibits superior electrochemical performance compared with directly etched counterparts [14].

◆ **Molten Salt Etching**

Molten salt approaches have emerged as promising alternatives capable of producing high-quality MXenes while reducing reliance on hazardous chemicals [15].

Advantages include:

- Controlled reaction kinetics.
- Lower defect densities.
- Potential scalability.

However, optimization of reaction temperatures and purification procedures remains necessary.

◆ **Electrochemical Etching**

Electrochemical synthesis techniques utilize external electrical potentials to selectively remove A-group elements from MAX phases [16].

Potential benefits include:

- Reduced environmental burden.
- Improved process controllability.
- Enhanced suitability for industrial automation.

Nevertheless, the requirement for specialized equipment currently limits widespread adoption.

Table 3. Comparative Analysis of Major MXene Synthesis Techniques

Synthesis Method	**Advantages**	**Limitations**	**Industrial Potential**
Hydrofluoric Acid Etching	High efficiency, well-established	Severe toxicity, structural damage	Moderate
In-Situ HF Generation	Improved safety, better intercalation	Multi-step processing	High
Molten Salt Etching	Lower defect density, tunable chemistry	Elevated temperatures required	High
Electrochemical Etching	Environmentally friendly, controllable	Equipment complexity	Moderate
Fluoride-Free Methods	Sustainable processing	Early-stage development	Emerging

Delamination and Surface Engineering

Following etching procedures, multilayer MXene structures frequently require delamination to generate few-layer or single-layer nanosheets suitable for electrochemical applications.

Delamination is commonly achieved through:

- Ultrasonication treatments,
- Organic molecule intercalation,
- Metal ion-assisted expansion,
- Mechanical agitation.

The resulting increase in accessible surface area significantly improves electrolyte penetration and charge storage capability [17].

Surface engineering further modifies MXene performance characteristics. Surface functional groups such as –OH, –F, and =O influence hydrophilicity, conductivity, and electrochemical behavior [18]. Consequently, strategies aimed at regulating surface chemistry have become central to MXene research.

4. Characterization Techniques

Comprehensive characterization is essential for establishing relationships between synthesis parameters, structural properties, and functional performance.

X-Ray Diffraction (XRD)

XRD remains one of the most widely employed techniques for confirming successful MXene formation [19].

Characteristic observations include:

- Reduction in MAX phase peak intensity.
- Shifts in the (002) diffraction peak.
- Increased interlayer spacing following etching.

Such changes provide evidence supporting effective removal of A-group layers.

Scanning Electron Microscopy (SEM)

SEM analysis facilitates examination of MXene morphology and surface architecture.

Typical SEM observations reveal:

- Accordion-like layered structures,
- Expanded interlayer regions,
- Morphological modifications following composite formation.

These features provide qualitative insights into exfoliation efficiency [20].

Transmission Electron Microscopy (TEM)

TEM enables nanoscale structural investigations involving:

- Layer thickness measurements,
- Crystallographic analysis,
- Visualization of individual nanosheets.

High-resolution TEM studies frequently demonstrate lattice integrity within exfoliated MXene structures [21].

X-Ray Photoelectron Spectroscopy (XPS)

XPS plays a critical role in determining:

- Surface elemental composition,
- Oxidation states,
- Functional group distributions.

Understanding surface chemistry is particularly important because electrochemical performance depends strongly upon terminal group characteristics [18].

Raman Spectroscopy

Raman spectroscopy provides information regarding:

- Structural disorder,
- Vibrational characteristics,
- Interfacial interactions within composites.

Shifts in Raman peaks often indicate successful hybridization with polymers or carbon-based nanomaterials [22].

Table 4. Characterization Techniques Employed in MXene Research

Technique	Information Obtained	Relevance to Device Performance
XRD	Crystal structure and interlayer spacing	Ion transport efficiency
SEM	Surface morphology	Electrolyte accessibility
TEM	Nanosheet thickness and lattice structure	Charge transfer pathways
XPS	Surface chemistry and oxidation states	Electrochemical activity
Raman Spectroscopy	Structural integrity and defects	Mechanical stability
FTIR Spectroscopy	Functional group identification	Surface interactions
EDS Mapping	Elemental distribution	Material homogeneity

Challenges in Characterization

Despite considerable advances, several characterization-related challenges persist.

First, oxidation during sample handling may alter MXene chemistry, thereby affecting analytical outcomes [7]. Second, distinguishing between surface terminations remains difficult due to overlapping spectral signatures [18]. Finally, inconsistencies in reporting standards complicate comparisons among independent investigations.

Addressing these challenges will require standardized characterization protocols and collaborative efforts aimed at improving reproducibility across laboratories.

 DOI: 10.36297/vw.jei.v8i2.406

5. MXene-Based Energy Storage Applications

The remarkable electrical conductivity, hydrophilic surface chemistry, and tunable interlayer spacing of MXenes have established them as one of the most promising classes of nanomaterials for advanced energy storage technologies. Recent investigations have demonstrated the potential of MXenes in supercapacitors, rechargeable batteries, hybrid energy systems, and emerging multifunctional energy devices [23]. Their ability to facilitate rapid electron transport while simultaneously accommodating ion intercalation processes contributes significantly to their superior electrochemical performance.

MXenes in Supercapacitors

Supercapacitors have attracted considerable attention owing to their high power density, rapid charge–discharge capability, and extended cycle life. However, the relatively low energy density associated with conventional carbon-based electrodes has motivated the search for alternative materials capable of overcoming these limitations.

MXenes exhibit several characteristics favorable for supercapacitor applications, including:

- Metallic electrical conductivity,
- Abundant electrochemically active sites,
- High volumetric density,
- Tunable surface functionalities,
- Excellent wettability in aqueous electrolytes.

The charge storage mechanism of MXene-based supercapacitors involves both electric double-layer capacitance and pseudocapacitive behavior resulting from reversible redox interactions occurring at surface termination sites [24].

$Ti_3C_2T_x$ MXene remains the most extensively investigated composition in this context. Experimental studies have demonstrated that controlling interlayer spacing through ion intercalation and composite engineering significantly enhances ion diffusion kinetics and capacitance retention [25].

Furthermore, hybridization with conducting polymers and carbonaceous nanostructures has emerged as an effective strategy for mitigating restacking effects while increasing the availability of electrochemically accessible surface area [26].

Table 5. Advantages of MXene-Based Supercapacitor Electrodes

Property	Engineering Significance
High electrical conductivity	Facilitates rapid electron transport
Hydrophilic surfaces	Enhances electrolyte accessibility
Tunable interlayer spacing	Improves ion diffusion pathways
Mechanical flexibility	Enables wearable energy devices
Pseudocapacitive behavior	Increases charge storage capability
Solution processability	Supports scalable fabrication methods

 DOI: 10.36297/vw.jei.v8i2.406

MXenes in Lithium-Ion Batteries

Lithium-ion batteries dominate the contemporary energy storage market owing to their favorable energy density and operational reliability. Nevertheless, increasing demands from electric transportation and grid-scale storage necessitate continuous improvements in electrode materials.

MXenes have emerged as attractive candidates for lithium-ion battery applications because their layered architectures facilitate efficient lithium-ion intercalation processes [27]. The metallic conductivity of MXenes further contributes to enhanced rate capability by minimizing internal resistance.

Several investigations have explored the incorporation of MXenes into composite electrodes designed to improve structural stability during repeated charge–discharge cycles. Such strategies include integration with silicon nanoparticles, transition metal oxides, and conductive carbon networks [28].

These hybrid systems often exhibit:

- Enhanced reversible capacity,
- Improved cycling stability,
- Superior rate performance,
- Reduced volume expansion effects.

However, challenges associated with oxidation susceptibility and nanosheet aggregation continue to require further investigation.

MXenes in Sodium-Ion Batteries

Sodium-ion batteries have emerged as promising alternatives to lithium-ion systems due to the natural abundance and lower cost of sodium resources. The larger ionic radius of sodium ions, however, imposes significant constraints on electrode materials.

The enlarged interlayer spacing characteristic of MXene structures offers favorable conditions for sodium-ion accommodation and transport [29]. Consequently, MXene-based anodes have demonstrated encouraging electrochemical characteristics including high reversible capacity and prolonged cycle life.

Surface engineering approaches involving heteroatom doping and interlayer expansion have further improved sodium-ion diffusion kinetics [30]. Such developments highlight the growing importance of MXenes in the pursuit of sustainable and economically viable energy storage technologies.

Table 6. Comparison of Battery Systems Utilizing MXene Electrodes

Parameter	**Lithium-Ion Batteries**	**Sodium-Ion Batteries**
Charge Carrier	Li^{+}	Na^{+}
Resource Availability	Moderate	High
Relative Cost	Higher	Lower
Ion Radius	Smaller	Larger
MXene Function	Intercalation host	Intercalation host

Major Challenge	Structural degradation	Slower ion diffusion
Future Potential	High	Very High

Hybrid Energy Storage Systems

Hybrid energy storage systems seek to combine the advantages associated with batteries and supercapacitors to achieve balanced performance characteristics involving both high energy density and high power density.

MXene nanomaterials have demonstrated considerable promise within such architectures due to their multifunctional electrochemical properties [31]. Their integration into asymmetric device configurations facilitates optimization of charge storage mechanisms while maintaining operational stability.

Recent investigations have reported encouraging results involving MXene-based hybrid capacitors exhibiting improved energy density without compromising rate capability [32]. Such developments may contribute significantly to future electric mobility systems and renewable energy infrastructures.

Flexible Energy Storage Devices

The increasing prevalence of wearable electronics has stimulated demand for energy storage systems capable of functioning under repeated mechanical deformation.

MXenes exhibit intrinsic characteristics favorable for flexible energy devices, including:

- Excellent electrical conductivity,
- High mechanical flexibility,
- Solution processability,
- Compatibility with polymeric substrates.

Flexible MXene-based supercapacitors have demonstrated stable electrochemical performance under bending and twisting conditions [33]. Integration with textile substrates has further enabled the development of wearable energy storage platforms suitable for smart healthcare applications.

Composite strategies involving polymers such as polyvinyl alcohol and polyaniline have contributed to improvements in both mechanical durability and electrochemical efficiency [34].

Table 7. Applications of MXene-Based Flexible Energy Storage Systems

Application	**Functional Requirement**	**Contribution of MXenes**
Smart Watches	Compact energy storage	High volumetric capacitance
Electronic Skin	Mechanical flexibility	Stable conductivity during deformation
Wearable Sensors	Lightweight design	Integration with flexible substrates
Smart Textiles	Washable energy units	Solution processabilit
Medical Monitoring Devices	Reliable operation	Enhanced electrochemical stability

 DOI: 10.36297/vw.jei.v8i2.406

Challenges in Energy Storage Applications

Despite substantial progress, several barriers continue to impede large-scale implementation of MXene-based energy storage systems.

Oxidation Stability

Exposure to oxygen and moisture may induce degradation processes that adversely affect conductivity and electrochemical activity [35].

Nanosheet Restacking

Strong van der Waals interactions promote aggregation, thereby reducing accessible surface area and limiting ion transport pathways [25].

Scalable Manufacturing

The transition from laboratory-scale synthesis to industrial production remains challenging due to cost considerations and safety concerns associated with certain etching procedures [12].

Environmental Considerations

The development of environmentally benign synthesis routes represents an important priority for sustainable commercialization efforts [15].

Addressing these limitations through interdisciplinary collaboration will be critical for realizing the full technological potential of MXene nanomaterials.

6. MXene-Based Flexible Electronics and Sensing Applications

Introduction to Flexible Electronics

The emergence of flexible and wearable electronic technologies has transformed the landscape of modern engineering. Unlike conventional rigid electronic systems, flexible electronics are designed to maintain functionality under various forms of mechanical deformation, including bending, stretching, twisting, and folding. Applications range from wearable healthcare monitoring devices to soft robotics, human–machine interfaces, and smart textiles [36].

The development of these systems requires materials possessing a unique combination of electrical conductivity, mechanical flexibility, environmental stability, and compatibility with scalable fabrication processes. MXene nanomaterials, particularly $Ti_3C_2T_x$, have demonstrated significant promise in meeting these requirements due to their two-dimensional morphology, metallic conductivity, and solution-processable nature [37].

MXene-Based Wearable Sensors

Wearable sensors have become increasingly important in healthcare monitoring, fitness tracking, and rehabilitation engineering. These devices convert physiological or environmental stimuli into measurable electrical signals.

MXene-based sensors have attracted considerable attention because of their:

- High electrical conductivity,
- Fast response characteristics,
- Excellent sensitivity,
- Mechanical adaptability,
- Ease of integration with flexible substrates.

Piezoresistive MXene sensors operate by monitoring resistance changes induced by external mechanical forces. The layered structure of MXenes enables efficient modulation of conductive pathways during deformation, thereby enhancing sensing performance [38].

Applications include:

- Pulse monitoring,
- Respiration tracking,
- Joint motion detection,
- Facial expression recognition,
- Human activity analysis.

Recent studies have reported MXene sensors exhibiting remarkable operational stability under thousands of loading–unloading cycles, highlighting their suitability for long-term wearable applications [39].

Table 8. Applications of MXene-Based Wearable Sensors

Application Area	**Physiological Parameter**	**Importance**
Cardiovascular Monitoring	Pulse rate	Early disease detection
Respiratory Monitoring	Breathing frequency	Sleep disorder analysis
Motion Tracking	Joint movement	Rehabilitation assessment
Speech Recognition	Throat vibration	Human–machine communication
Facial Expression Detection	Skin deformation	Emotion analysis
Fitness Monitoring	Physical activity	Performance optimization

Electronic Skin (E-Skin)

Electronic skin represents one of the most sophisticated applications of flexible electronics. These systems aim to emulate the sensing capabilities of biological skin by detecting pressure, strain, temperature, and tactile stimuli [40].

MXenes offer several advantages for e-skin applications:

- Superior conductivity,
- High sensitivity toward external pressure,
- Compatibility with stretchable polymers,
- Biocompatibility potential,
- Thin-film processability.

MXene–polymer composites have been successfully employed in pressure-sensitive e-skin platforms capable of detecting subtle physiological signals such as arterial pulses and vocal cord vibrations [41].

The incorporation of self-healing polymers into MXene architectures has further expanded the potential of these systems by improving device longevity and reliability [42].

Flexible Strain and Pressure Sensors

Strain sensors play a critical role in wearable healthcare systems, robotics, and structural monitoring applications.

MXene-based strain sensors have demonstrated:

- Broad sensing ranges,
- Rapid response times,
- High gauge factors,
- Excellent repeatability.

The performance of such sensors depends strongly upon:

- Interfacial adhesion,
- Nanosheet orientation,
- Composite architecture,
- Surface functionalization.

Pressure sensors fabricated using porous MXene frameworks have exhibited enhanced compressibility and sensitivity due to the presence of interconnected conductive networks [43].

Table 9. Performance Characteristics of MXene-Based Flexible Sensors

Sensor Type	**Sensing Mechanism**	**Major Advantages**
Strain Sensor	Resistance variation	High gauge factor
Pressure Sensor	Conductive pathway modulation	Wide pressure range
Tactile Sensor	Surface contact detection	Rapid response
Respiratory Sensor	Chest expansion monitoring	Non-invasive measurement
Pulse Sensor	Arterial signal detection	High sensitivity

Electromagnetic Interference Shielding

The increasing density of electronic devices has intensified concerns regarding electromagnetic interference (EMI), which may compromise device functionality and communication quality.

Materials utilized for EMI shielding must possess:

- High electrical conductivity,
- Structural integrity,
- Lightweight characteristics,
- Processability.

MXenes satisfy these criteria and have demonstrated outstanding shielding effectiveness across broad frequency ranges [44].

The layered morphology of MXenes promotes multiple reflection and absorption mechanisms responsible for attenuating electromagnetic radiation. Furthermore, hybridization with polymers enables the fabrication of flexible shielding materials suitable for wearable applications [45].

Potential applications include:

- Aerospace electronics,
- Medical instrumentation,
- Telecommunications,
- Consumer electronics.

Table 10. Advantages of MXenes for EMI Shielding Applications

Property	**Engineering Benefit**
High conductivity	Efficient reflection of electromagnetic waves
Layered structure	Enhanced absorption mechanisms
Low density	Lightweight shielding materials
Mechanical flexibility	Wearable electronics compatibility
Solution processability	Scalable manufacturing potential

Smart Textiles

Smart textiles integrate sensing, communication, and energy functionalities directly into fabrics.

The incorporation of MXenes into textile substrates has enabled the development of multifunctional systems capable of:

- Monitoring physiological parameters,
- Storing energy,
- Providing thermal management,
- Shielding electromagnetic radiation.

MXene-coated fabrics exhibit excellent flexibility and maintain conductivity under repeated bending conditions [46].

Several fabrication techniques have been employed, including:

- Dip coating,
- Spray coating,
- Vacuum filtration,
- Layer-by-layer assembly.

These approaches facilitate large-area processing while preserving the intrinsic characteristics of textile materials.

Flexible Displays and Transparent Electronics

The evolution of foldable electronic devices has stimulated interest in transparent conductive materials capable of replacing conventional brittle electrodes.

 DOI: 10.36297/vw.jei.v8i2.406

Although further optimization remains necessary, MXene thin films have demonstrated promising optical and electrical characteristics relevant to:

- Flexible displays,
- Transparent touch panels,
- Wearable optoelectronics.

Challenges associated with oxidation stability and transparency optimization continue to motivate ongoing research efforts [47].

Challenges and Future Perspectives

Despite remarkable progress, several challenges remain before MXene-based flexible electronics achieve widespread commercialization.

Oxidation Susceptibility

Exposure to oxygen and moisture can degrade MXene conductivity and compromise device performance [35].

Long-Term Mechanical Stability

Repeated deformation may induce structural defects affecting sensing accuracy and durability.

Biocompatibility Assessment

Further investigations are required to establish the long-term safety of MXene-based wearable systems intended for direct skin contact [48].

Large-Scale Manufacturing

Scalable and environmentally sustainable production techniques remain essential for industrial adoption.

Addressing these limitations through interdisciplinary collaboration involving materials scientists, biomedical engineers, and manufacturing specialists will accelerate the translation of MXene technologies into practical applications.

Table 11. Major Challenges Associated with MXene-Based Flexible Electronics

Challenge	**Impact on Device Performance**	**Potential Solutions**
Oxidation	Conductivity loss	Surface passivation
Mechanical fatigue	Reduced operational lifespan	Polymer reinforcement
Restacking	Lower sensitivity	Spacer incorporatio
Manufacturing cost	Limited commercialization	Process optimization
Safety concerns	Regulatory barriers	Comprehensive biocompatibility studies

7. Challenges, Future Perspectives, and Conclusion

Challenges in MXene Commercialization

Despite the remarkable progress achieved in MXene research during the past decade, several scientific and engineering challenges continue to impede their widespread industrial adoption. Addressing these limitations remains critical for translating laboratory-scale discoveries into commercially viable technologies.

Oxidation and Environmental Stability

One of the most significant barriers affecting MXene applications is their susceptibility to oxidation under ambient conditions. Exposure to oxygen, moisture, and elevated temperatures can result in the degradation of surface functionalities and deterioration of electrical conductivity. This phenomenon adversely influences device reliability and long-term operational performance.

Several approaches have been proposed to mitigate oxidation-induced degradation, including low-temperature storage, surface passivation strategies, antioxidant incorporation, and polymer encapsulation. However, standardized stabilization protocols remain an active area of investigation.

Nanosheet Restacking

MXene nanosheets exhibit strong interlayer interactions that frequently lead to aggregation during processing. Restacking decreases accessible surface area and obstructs ion transport pathways, thereby limiting electrochemical performance.

Current strategies aimed at overcoming this challenge include:

- Interlayer engineering using metal ions,
- Polymer intercalation,
- Carbon nanotube incorporation,
- Porous architecture design,
- Three-dimensional framework fabrication.

These approaches have demonstrated promising outcomes; however, scalable implementation remains challenging.

Sustainable and Scalable Synthesis

Traditional MXene synthesis protocols frequently involve hydrofluoric acid or fluoride-containing reagents, raising concerns regarding safety and environmental sustainability. Consequently, substantial research efforts have focused on developing greener synthesis methodologies.

Electrochemical etching techniques, molten salt approaches, and fluoride-free processing strategies have emerged as potential alternatives capable of supporting large-scale production. Recent investigations have reported encouraging results involving non-toxic electrolytes that maintain material quality while improving sustainability.

Standardization and Reproducibility

Variations in synthesis procedures, characterization techniques, and reporting methodologies complicate comparisons among independent investigations. Establishing internationally accepted standards for MXene preparation and performance evaluation will be essential for accelerating commercialization efforts.

Table 12. Major Challenges and Potential Solutions for MXene Technologies

Challenge	**Impact**	**Proposed Solutions**
Oxidation susceptibility	Conductivity degradation	Surface passivation and encapsulation

Nanosheet restacking	Reduced ion accessibility	Intercalation and porous architectures
Hazardous synthesis chemicals	Environmental and safety concerns	Green etching methodolog
Manufacturing scalability	Limited industrial adoption	Continuous processing systems
Lack of standardization	Reduced reproducibility	International reporting guidelines
Long-term reliability concerns	Device instability	Accelerated aging investigations

8. Future Perspectives

The future development of MXene technologies is expected to benefit substantially from interdisciplinary collaborations integrating nanotechnology, artificial intelligence, computational materials science, and advanced manufacturing.

Artificial Intelligence-Assisted Materials Discovery

Machine learning techniques are increasingly being employed to predict structure–property relationships within emerging nanomaterials. The integration of artificial intelligence into MXene research may facilitate:

- Identification of novel MXene compositions,
- Prediction of optimal surface functionalization strategies,
- Accelerated screening of electrochemical properties,
- Optimization of synthesis parameters.

Such approaches have the potential to significantly reduce experimental costs and development timelines.

Multifunctional Hybrid Architectures

Future investigations are expected to emphasize the development of multifunctional systems integrating MXenes with:

- Conductive polymers,
- Graphene derivatives,
- Metal–organic frameworks,
- Carbon nanotubes,
- Biomaterials.

These hybrid architectures may enable simultaneous achievement of high conductivity, enhanced mechanical robustness, improved environmental stability, and superior electrochemical performance.

Flexible and Wearable Healthcare Technologies

The growing demand for personalized healthcare solutions presents substantial opportunities for MXene-enabled wearable devices. Future systems may incorporate:

- Real-time physiological monitoring,
- Self-powered sensing mechanisms,

- Wireless communication capabilities,
- Smart therapeutic platforms.

The exceptional sensitivity demonstrated by MXene-based sensors suggests considerable promise in this domain.

Sustainable Manufacturing

Environmental sustainability is increasingly recognized as an essential consideration in nanotechnology development. Consequently, future MXene research should prioritize:

- Reduction of hazardous reagents,
- Resource-efficient processing,
- Life-cycle assessment studies,
- Recycling and end-of-life management strategies.

Such initiatives will contribute to the responsible commercialization of MXene technologies.

Table 13. Emerging Research Directions in MXene Engineering

Research Area	Future Opportunities
Green synthesis methods	Environmentally responsible production
AI-assisted material design	Accelerated discovery and optimization
Hybrid nanocomposites	Multifunctional device performance
Flexible bioelectronics	Personalized healthcare applications
Advanced energy systems	Grid-scale and wearable energy storage
Smart textiles	Integrated sensing and energy functionalities
High-frequency shielding materials	Aerospace and telecommunications applications

Conclusion

MXenes have emerged as one of the most promising classes of two-dimensional nanomaterials for next-generation energy storage systems and flexible electronic applications. Their distinctive combination of metallic conductivity, hydrophilic surfaces, tunable chemistry, and layered architectures has enabled remarkable advances across a wide spectrum of technologies including supercapacitors, rechargeable batteries, wearable sensors, electronic skin, smart textiles, and electromagnetic interference shielding systems.

The present review has critically examined the evolution of MXene synthesis methodologies, characterization techniques, and engineering applications relevant to sustainable energy and flexible electronics. Comparative analyses reveal that $Ti_3C_2T_x$ MXene remains the most extensively investigated composition owing to its favorable electrochemical characteristics and compatibility with diverse fabrication strategies. Nevertheless, emerging MXene families continue to expand the functional landscape of these materials.

Despite substantial progress, several barriers continue to hinder widespread industrial implementation. Oxidation susceptibility, nanosheet restacking, safety concerns associated with conventional synthesis approaches, and challenges related to scalable manufacturing represent critical issues requiring continued attention. Addressing these limitations through interdisciplinary collaborations will be essential for facilitating successful commercialization.

Future developments are expected to focus increasingly upon environmentally sustainable synthesis routes, artificial intelligence-assisted materials discovery, multifunctional composite architectures, and healthcare-oriented wearable technologies. Such innovations may enable MXenes to play a transformative role in advancing the next generation of intelligent, efficient, and sustainable engineering systems.

The exceptional versatility exhibited by MXene nanomaterials suggests that they will remain at the forefront of nanotechnology research for the foreseeable future. Continued efforts directed toward understanding their fundamental properties while simultaneously addressing practical constraints will determine the extent to which MXenes contribute to future technological revolutions.

References

1. M. Naguib, M. W. Barsoum, and Y. Gogotsi, "Ten Years of Progress in the Synthesis and Development of MXenes," Advanced Materials, vol. 33, no. 39, p. 2103393, 2021. doi: 10.1002/adma.202103393.

2. M. Naguib, M. Kurtoglu, V. Presser, J. Lu, J. Niu, M. Heon, L. Hultman, Y. Gogotsi, and M. W. Barsoum, "Two-Dimensional Nanocrystals Produced by Exfoliation of Ti_3AlC_2," Advanced Materials, vol. 23, no. 37, pp. 4248–4253, 2011.

3. B. Anasori, M. R. Lukatskaya, and Y. Gogotsi, "2D Metal Carbides and Nitrides (MXenes) for Energy Storage," Nature Reviews Materials, vol. 2, p. 16098, 2017.

4. M. R. Lukatskaya, S. M. Bak, X. Yu, X.-Q. Yang, M. W. Barsoum, and Y. Gogotsi, "Probing the Mechanism of High Capacitance in 2D Titanium Carbide Using In Situ X-Ray Absorption Spectroscopy," Advanced Energy Materials, vol. 5, no. 15, p. 1500589, 2015.

5. Y. Wang, Y. Yue, F. Cheng, Y. Cheng, B. Ge, N. Liu, and Y. Gao, "$Ti_3C_2T_x$ MXene-Based Flexible Piezoresistive Physical Sensors," ACS Nano, vol. 16, no. 2, pp. 1734–1758, 2022. doi: 10.1021/acsnano.1c09925.

6. Y. Gogotsi and B. Anasori, "The Rise of MXenes," ACS Nano, vol. 13, no. 8, pp. 8491–8494, 2019.

7. M. Alhabeb, K. Maleski, B. Anasori, P. Lelyukh, L. Clark, S. Sin, and Y. Gogotsi, "Guidelines for Synthesis and Processing of Two-Dimensional Titanium Carbide ($Ti_3C_2T_x$ MXene)," Chemistry of Materials, vol. 29, no. 18, pp. 7633–7644, 2017.

8. M. Naguib, V. N. Mochalin, M. W. Barsoum, and Y. Gogotsi, "25th Anniversary Article: MXenes: A New Family of Two-Dimensional Materials," Advanced Materials, vol. 26, no. 7, pp. 992–1005, 2014.

9. Y. Dall'Agnese, P.-L. Taberna, Y. Gogotsi, and P. Simon, "Two-Dimensional Vanadium Carbide (MXene) as Positive Electrode for Sodium-Ion Capacitors," Journal of Physical Chemistry Letters, vol. 6, no. 12, pp. 2305–2309, 2015.

10. M. R. Lukatskaya, O. Mashtalir, C. E. Ren, Y. Dall'Agnese, P. Rozier, P.-L. Taberna, M. Naguib, P. Simon, M. W. Barsoum, and Y. Gogotsi, "Cation Intercalation and High Volumetric Capacitance of Two-Dimensional Titanium Carbide," Science, vol. 341, no. 6153, pp. 1502–1505, 2013.

11. B. Ahmed, D. H. Anjum, M. N. Hedhili, Y. Gogotsi, and H. N. Alshareef, "H_2O-Assisted Delamination of Large Stacked $Ti_3C_2T_x$ MXene Sheets," Nanoscale, vol. 8, no. 14, pp. 7580–7587, 2016.

12. M. Alhabeb, K. Maleski, B. Anasori, P. Lelyukh, L. Clark, S. Sin, and Y. Gogotsi, "Synthesis and Processing of 2D Titanium Carbide ($Ti_3C_2T_x$ MXene)," Chemistry of Materials, vol. 29, no. 18, pp. 7633–7644, 2017.

13. M. Ghidiu, M. R. Lukatskaya, M.-Q. Zhao, Y. Gogotsi, and M. W. Barsoum, "Conductive Two-Dimensional Titanium Carbide 'Clay' with High Volumetric Capacitance," Nature, vol. 516, pp. 78–81, 2014.

14. C. Eames and M. S. Islam, "Ion Intercalation into Two-Dimensional Transition-Metal Carbides: Global Screening for New High-Capacity Battery Materials," Journal of the American Chemical Society, vol. 136, no. 46, pp. 16270–16276, 2014.

15. M. Li, J. Lu, K. Luo, Y. Li, K. Chang, K. Chen, J. Zhou, J. Rosen, M. Hultman, P. Eklund, P. O. Å. Persson, and L. F. Hultman, "Element Replacement Approach by Reaction with Lewis Acidic Molten Salts to Synthesize Nanolaminated MAX Phases and MXenes," Journal of the American Chemical Society, vol. 141, no. 11, pp. 4730–4737, 2019.

16. A. VahidMohammadi, J. Rosen, and Y. Gogotsi, "The World of Two-Dimensional Carbides and Nitrides (MXenes)," Science, vol. 372, no. 6547, eabf1581, 2021.

17. O. Mashtalir, M. Naguib, V. N. Mochalin, Y. Dall'Agnese, M. Heon, M. W. Barsoum, and Y. Gogotsi, "Intercalation and Delamination of Layered Carbides and Carbonitrides," Nature Communications, vol. 4, p. 1716, 2013.

18. B. Anasori, Y. Gogotsi, and V. N. Mochalin, "2D Metal Carbides and Nitrides (MXenes) for Energy Storage," Nature Reviews Materials, vol. 2, p. 16098, 2017.

19. J. Halim, M. Lukatskaya, K. Cook, J. Lu, C. Smith, L. Näslund, S. May, L. Hultman, Y. Gogotsi, P. Eklund, and M. W. Barsoum, "Transparent Conductive Two-Dimensional Titanium Carbide Epitaxial Thin Films," Chemistry of Materials, vol. 26, no. 7, pp. 2374–2381, 2014.

20. Y. Xie and P. R. C. Kent, "Hybrid Density Functional Study of Structural and Electronic Properties of Functionalized $Ti_{n+1}X_n$ (X = C, N) Monolayers," Physical Review B, vol. 87, p. 235441, 2013.

21. M. Naguib, J. Halim, J. Lu, K. Cook, L. Hultman, Y. Gogotsi, and M. W. Barsoum, "New Two-Dimensional Niobium and Vanadium Carbides as Promising Materials for Li-Ion Batteries," Journal of the American Chemical Society, vol. 135, no. 43, pp. 15966–15969, 2013.

22. S. J. Kim, M. Naguib, M. Zhao, C. Zhang, H. Jung, M. K. Lee, M. Barsoum, and Y. Gogotsi, "High Mass Loading, Binder-Free MXene Anodes for High Areal Capacity Li-Ion Batteries," Electrochimica Acta, vol. 163, pp. 246–251, 2015.

23. Y. Gogotsi and B. Anasori, "The Rise of MXenes," ACS Nano, vol. 13, no. 8, pp. 8491–8494, 2019.

24. M. R. Lukatskaya, O. Mashtalir, C. E. Ren, Y. Dall'Agnese, P. Rozier, P.-L. Taberna, M. Naguib, P. Simon, M. W. Barsoum, and Y. Gogotsi, "Cation Intercalation and High Volumetric Capacitance of Two-Dimensional Titanium Carbide," Science, vol. 341, no. 6153, pp. 1502–1505, 2013.

25. J. Wang, H. Liu, and X. Zhao, "Progress in Surface and Interlayer Distance Modulated 2D Ti_3C_2 MXenes for Potential Flexible Supercapacitors: A Review," Applied Materials Today, vol. 34, p. 101942, 2023.

26. Y. Dall'Agnese, M. Naguib, Y. Gogotsi, M. W. Barsoum, and P. Simon, "MXene-Based Electrochemical Capacitors and Pseudocapacitors," Journal of Power Sources, vol. 306, pp. 510–515, 2016.

27. C. Eames and M. S. Islam, "Ion Intercalation into Two-Dimensional Transition-Metal Carbides," Journal of the American Chemical Society, vol. 136, no. 46, pp. 16270–16276, 2014.

28. S. J. Kim, M. Naguib, M. Zhao, C. Zhang, H. Jung, M. K. Lee, M. Barsoum, and Y. Gogotsi, "Binder-Free MXene Anodes for Li-Ion Batteries," Electrochimica Acta, vol. 163, pp. 246–251, 2015.

29. Y. Dall'Agnese, P.-L. Taberna, Y. Gogotsi, and P. Simon, "Vanadium Carbide MXene for Sodium-Ion Capacitors," Journal of Physical Chemistry Letters, vol. 6, no. 12, pp. 2305–2309, 2015.

30. A. VahidMohammadi, J. Rosen, and Y. Gogotsi, "The World of Two-Dimensional Carbides and Nitrides (MXenes)," Science, vol. 372, no. 6547, eabf1581, 2021.

31. J. Pang, R. G. Mendes, A. Bachmatiuk, L. Zhao, H.-Q. Ta, U. Gemming, H. Liu, Z. Liu, and M. H. Rümmeli, "Applications of 2D MXenes in energy conversion and storage systems," Chemical Society Reviews, vol. 48, no. 1, pp. 72–133, 2019.

32. J. Ran, G. Gao, F.-T. Li, T.-Y. Ma, A. Du, and S.-Z. Qiao, "Ti_3 C_2 MXene co-catalyst on metal sulfide photo-absorbers for enhanced visible-light photocatalytic hydrogen production," Nature Communications, vol. 8, p. 13907, 2017.

33. A. VahidMohammadi, A. Hadjikhani, S. Shahbazmohamadi, and M. Beidaghi, "MXene-based energy storage devices," Journal of Materials Chemistry A, vol. 7, no. 29, pp. 17595–17619, 2019.

34. Y. Xie, Y. Dall'Agnese, M. Naguib, M. W. Barsoum, Y. Gogotsi, P. R. C. Kent, and H. Xiao, "Prediction and characterization of MXene nanosheet anodes for non-lithium-ion batteries," ACS Nano, vol. 8, no. 9, pp. 9606–9615, 2014.

35. C. Zhang, B. Anasori, A. Seral-Ascaso, S.-H. Park, N. McEvoy, A. Shmeliov, G. S. Duesberg, J. N. Coleman, Y. Gogotsi, and V. Nicolosi, "Transparent, flexible, and conductive 2D titanium carbide (MXene) films with high volumetric capacitance," Advanced Materials, vol. 29, no. 36, p. 1702678, 2017.

36. K. Hantanasirisakul and Y. Gogotsi, "Electronic and optical properties of 2D transition metal carbides and nitrides (MXenes)," Advanced Materials, vol. 30, no. 52, p. 1804779, 2018.

37. J. Halim, S. Kota, M. R. Lukatskaya, M. Naguib, M.-Q. Zhao, E. J. Moon, J. Pitock, J. Nanda, S. J. May, Y. Gogotsi, P. Eklund, M. W. Barsoum, and V. N. Mochalin, "Synthesis and characterization of 2D molybdenum carbide (MXene)," Advanced Functional Materials, vol. 26, no. 18, pp. 3118–3127, 2016.

38. M. Shahzad, A. L. Ahmad, M. Moztahida, E. J. Navid, S. W. Hwang, and C. M. Koo, "Electromagnetic interference shielding with 2D transition metal carbides (MXenes)," Science, vol. 353, no. 6304, pp. 1137–1140, 2016.

39. B. Ahmed, M. N. Hedhili, D. H. Anjum, and H. N. Alshareef, "MXenes as emerging materials for electrochemical energy storage," Nano Energy, vol. 34, pp. 249–271, 2017.

40. M.-Q. Zhao, X. Xie, C. E. Ren, T. Makaryan, B. Anasori, G. Wang, and Y. Gogotsi, "Hollow MXene spheres and 3D macroporous MXene frameworks for Na-ion storage," Advanced Materials, vol. 29, no. 37, p. 1702410, 2017.

41. K. Maleski, V. N. Mochalin, and Y. Gogotsi, "Dispersions of two-dimensional titanium carbide MXene in organic solvents," Chemistry of Materials, vol. 29, no. 4, pp. 1632–1640, 2017.

42. S. J. Kim, H. Koh, C. E. Ren, O. Kwon, K. Maleski, C. K. Cho, H.-T. Choi, Y. Kim, N. Lu, J. Kim, and Y. Gogotsi, "Metallic Ti_3 C_2 T_x MXene gas sensors with ultrahigh signal-to-noise ratio," ACS Nano, vol. 12, no. 2, pp. 986–993, 2018.

43. X. Zhan, C. Si, J. Zhou, and Z. Sun, "MXene and MXene-based composites: synthesis, properties and environment-related applications," Nanoscale Horizons, vol. 5, no. 2, pp. 235–258, 2020.

44. H. Lin, X. Wang, L. Yu, Y. Chen, and J. Shi, "Two-dimensional ultrathin MXene ceramic nanosheets for photothermal conversion," Nano Letters, vol. 17, no. 1, pp. 384–391, 2017.

45. Y. Wang, Y. Yue, F. Cheng, Y. Cheng, B. Ge, N. Liu, and Y. Gao, "Ti_3 C_2 T_x MXene-based flexible piezoresistive physical sensors," ACS Nano, vol. 16, no. 2, pp. 1734–1758, 2022. doi: 10.1021/acsnano.1c09925. (American Chemical Society Publications)

46. S. Hajian, D. Maddipatla, B. B. Narakathu, and M. Z. Atashbar, "MXene-based flexible sensors: A review," Frontiers in Sensors, vol. 3, p. 1006749, 2022. doi: 10.3389/fsens.2022.1006749. (Frontiers)

 DOI: 10.36297/vw.jei.v8i2.406

47. S. Lee, E. H. Kim, W. Kim, S. H. Kim, Y. Kim, and J. H. Cho, "Polymer-laminated $Ti_3C_2T_x$ MXene electrodes for transparent and flexible field-driven electronics," ACS Nano, vol. 15, no. 5, pp. 8940–8952, 2021. (American Chemical Society Publications)

48. A. Iqbal, T. Hassan, S. M. Naqvi, Y. Gogotsi, and C. M. Koo, "MXenes for multispectral electromagnetic shielding," Nature Reviews Electrical Engineering, vol. 1, pp. 180–198, 2024. (Nature)

49. H. Li, R. Fan, B. Zou, J. Yan, Q. Shi, and G. Guo, "Roles of MXenes in biomedical applications: recent developments and prospects," Journal of Nanobiotechnology, vol. 21, p. 73, 2023. (Springer Link)

50. X. Xu, X. Ding, J. Wang, and Y. Li, "Status and prospects of MXene-based nanoelectronic devices," Matter, vol. 6, no. 4, pp. 1063–1092, 2023.