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A Review on Comparative Studies of Graphene and MXene-based 2D Materials: Properties, Synthesis, and Applications

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ABSTRACT

Graphene and MXenes are among the most promising two-dimensional (2D) nanomaterials owing to their exceptional structural, electrical, thermal, mechanical, and chemical properties, which have enabled significant advancements across various scientific and technological fields. This review presents a comprehensive comparative analysis of graphene and MXene-based materials with emphasis on their crystal structures, synthesis techniques, physicochemical properties, and emerging applications. Various synthesis approaches, including mechanical exfoliation, chemical vapor deposition, liquid-phase exfoliation, and selective chemical etching, are discussed in relation to their influence on material quality and scalability. The review further compares the performance of graphene and MXenes in gas sensing, biosensing, energy storage, flexible electronics, electromagnetic interference shielding, catalysis, environmental remediation, and biomedical applications. While graphene exhibits remarkable electrical conductivity, high carrier mobility, and mechanical strength, MXenes offer abundant surface functional groups, superior hydrophilicity, excellent electrochemical activity, and enhanced surface reactivity, making them particularly attractive for sensing and energy-related technologies. Recent advances in material functionalization, hybrid nanocomposites, and device fabrication are also highlighted to demonstrate improvements in sensitivity, selectivity, stability, and multifunctionality. Finally, the review discusses current challenges, including scalable synthesis, long-term environmental stability, oxidation resistance, and commercial implementation, while outlining future research directions for developing high-performance, sustainable, and application-specific 2D material systems.
Keywords: Synthesis, Applications, Graphene, Comparative Study, Mxene, 2D Materials, Flexible Electronics, Mechanical, And Chemical Properties.

1. INTRODUCTION

Two-dimensional (2D) nanomaterials have emerged as one of the most transformative classes of materials in modern materials science because of their exceptional electrical, mechanical, thermal, and chemical properties. Among these materials, graphene and MXenes have attracted significant research attention due to their outstanding performance across a wide range of technological applications, including electronics, energy storage, biomedical engineering, environmental monitoring, catalysis, and sensing technologies (Stankovich et al., 2006; Tian et al., 2018; Pandey et al., 2024). Their atomically thin layered structures provide a high specific surface area, superior electrical conductivity, excellent flexibility, and remarkable chemical stability, making them ideal candidates for next-generation multifunctional devices. As industries continue to demand lightweight, high-performance, and sustainable materials, graphene- and MXene-based nanomaterials have become increasingly important for advanced engineering applications (Bhaviripudi et al., 2010; Li et al., 2021).

Graphene, a single atomic layer of carbon atoms arranged in a two-dimensional honeycomb lattice, was first isolated in 2004 and has since revolutionized nanotechnology research. It possesses extraordinary electron mobility, high tensile strength, excellent thermal conductivity, and optical transparency, enabling its integration into flexible electronics, transparent conductive films, wearable devices, batteries, supercapacitors, and biomedical systems (Wang et al., 2020; Tian et al., 2018; Baker et al., 2024). Various synthesis techniques such as mechanical exfoliation, chemical vapor deposition (CVD), chemical reduction of graphene oxide, and laser-induced graphene have been developed to produce graphene with controlled morphology and high quality (Bhaviripudi et al., 2010; Lin et al., 2014). Despite these advantages, challenges such as scalable manufacturing, aggregation of nanosheets, and limited surface functionalization continue to influence its practical implementation.

Recent developments in nanomaterial synthesis have focused on improving the scalability, quality, and environmental sustainability of graphene and MXene production. While conventional methods such as mechanical exfoliation, chemical vapor deposition (CVD), and hydrofluoric acid (HF) etching remain widely employed, recent studies have introduced advanced techniques including laser-induced graphene (LIG), electrochemical exfoliation, plasma-enhanced CVD, fluoride-free etching, molten salt etching, and electrochemical synthesis.

These approaches aim to reduce processing cost, improve material quality, enhance safety, and facilitate large-scale industrial production (Verger et al., 2019; Lin et al., 2014; Pandey et al., 2024).

MXenes represent a relatively newer family of two-dimensional transition metal carbides, nitrides, and carbonitrides synthesized by selectively etching the A-layer from MAX phase precursors. Since their discovery, MXenes have demonstrated remarkable metallic conductivity, hydrophilic surfaces, abundant surface functional groups, and tunable electrochemical properties, making them highly attractive for energy storage devices, electromagnetic shielding, catalysis, water purification, biosensors, and wearable electronics (Pandey et al., 2024; Mehdi Aghaei et al., 2021; Xia et al., 2023). Unlike graphene, MXenes possess abundant terminal groups such as –O, –OH, and –F, which significantly improve their interaction with surrounding molecules and enhance surface reactivity for sensing and catalytic applications (Li et al., 2021; Zhang et al., 2022).

Among the numerous applications of graphene and MXenes, gas sensing has become one of the fastest-growing research areas because of the increasing need for rapid, sensitive, and selective detection of hazardous gases in healthcare, industrial safety, environmental monitoring, and smart wearable technologies (Dhall et al., 2021; Ryabtsev et al., 1999; Cho et al., 2021). Conventional semiconductor metal oxide gas sensors generally require elevated operating temperatures and consume considerable power. In contrast, graphene- and MXene-based sensors exhibit excellent room-temperature sensing performance, rapid response and recovery times, high sensitivity, and superior flexibility suitable for portable and wearable devices (Doan et al., 2020; Singh et al., 2017; Mehdi Aghaei et al., 2021). Recent studies have demonstrated remarkable sensing performance for gases including ammonia (NH_3), nitrogen dioxide (NO_2), hydrogen sulfide (H_2S), carbon dioxide (CO_2), volatile organic compounds (VOCs), ethanol, acetone, and hydrogen using graphene and MXene nanocomposites (Tang et al., 2024; Govind et al., 2024; Feng et al., 2024; Lu et al., 2024).

The sensing performance of these materials can be further enhanced through nanocomposite engineering and surface functionalization. Researchers have successfully incorporated metal oxides, conducting polymers, quantum dots, metal-organic frameworks (MOFs), and noble metal nanoparticles with graphene and MXenes to improve selectivity, stability, humidity resistance, and gas adsorption capability (Casanova-Chafer et al., 2024; Malathi et al., 2024; Pan et al., 2024; Li et al., 2021). Similarly, MXene-based hybrid structures integrated with polymers and transition metal oxides have shown enhanced electrical conductivity, larger active surface area, and improved charge-transfer characteristics, making them highly efficient for chemical sensing and electrochemical applications (Wu et al., 2023; Vaishag et al., 2024; Feng et al., 2024).

Beyond sensing applications, graphene and MXenes have demonstrated remarkable potential in energy storage technologies, including lithium-ion batteries, sodium-ion batteries, supercapacitors, fuel cells, and flexible energy devices because of their excellent electrical conductivity and rapid ion transport characteristics (Pandey et al., 2024). In biomedical engineering, graphene-based nanomaterials have been extensively explored for biosensors, drug delivery systems, tissue engineering, and cancer therapy, while MXenes have emerged as promising materials for bioimaging, photothermal therapy, antibacterial coatings, and electrochemical biosensors owing to their biocompatibility and versatile surface chemistry (Shen et al., 2012; Vaishag et al., 2023; Vaishag et al., 2024). Furthermore, both materials have gained increasing attention in flexible electronics, wearable healthcare devices, electromagnetic interference shielding, photocatalysis, wastewater treatment, and environmental remediation because of their multifunctional characteristics.

Although graphene and MXenes possess many similar advantages, they differ significantly in crystal structure, synthesis methods, electrical behavior, mechanical strength, chemical stability, hydrophilicity, surface chemistry, and application-specific performance. Graphene generally exhibits higher intrinsic carrier mobility and mechanical strength, whereas MXenes provide superior hydrophilicity, abundant functional groups, and enhanced electrochemical activity, making them particularly suitable for sensing and energy-related applications (Zhang et al., 2022; Xia et al., 2023; Mehdi Aghaei et al., 2021). Understanding these similarities and differences is essential for selecting the most appropriate material for specific engineering and biomedical applications.

Therefore, this review presents a comprehensive comparative study of graphene and MXene-based two-dimensional materials, focusing on their structural characteristics, physicochemical properties, conventional and emerging synthesis techniques, functionalization strategies, and diverse engineering applications. The review critically compares their advantages, limitations, and recent research developments across energy storage, gas sensing, biomedical engineering, environmental remediation, flexible electronics, and wearable technologies. Finally, the paper discusses current challenges, emerging trends, and future research directions that will support the development of next-generation graphene- and MXene-based multifunctional devices.

Although numerous review articles discuss graphene and MXenes separately, only a limited number provide a comprehensive comparison of their synthesis routes, structure–property relationships, and application-specific performance using recent literature. Furthermore, the latest environmentally friendly and scalable synthesis techniques have not been critically compared in a single review. This review addresses this gap by providing an updated comparison of conventional and emerging synthesis strategies together with their influence on material properties and applications.

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2. STRUCTURE

The flat molecular bonds represented by the structural formula in 2-dimensional materials are the result of covalent bonds. Thin crystalline solids with interlayer van der Waals and covalent bonds characterize these materials. Here we'll go over the molecular blueprints of graphene and Mxene.

2.1. Graphene: In Fig. 1, we can see that the carbon atoms in graphene are arranged in a honeycomb pattern, giving the material the appearance of a 2D hexagonal carbon atom with hybrid s p2 bonding, much like chicken wire (Meyer et al., 2008). The interlayer interactions in graphene are strengthened by the σ bonds, which also serve to connect the various layers of the material. Scientists have found many uses for graphene, including its oxide and reduced forms. It is possible to create graphene by surface modification according to the application, and it may be bound into balls, rolled into tubes, or stacked to form graphite again (Obodo et al., 2019; Soldano et al., 2010; Abergel et al., 2010). The structure of graphene is seen in Figure 1. The weight of graphene is a mere 0.77 mg/m2 and it is very thin, with just one carbon atom thick (~0.34 nm). Since helium atoms are unable to pass through it, it is very impermeable (Zhan et al., 2020).
The two-dimensional electron gas (2DEG) with great mobility is made possible by the graphene structure mentioned above. Graphene sheets are able to reach a mobility of up to 15,000-2,000 cm2/Vs due to the delocalization of π-bonding electrons, which is limited during bilayer growth by interactions with the substrate, any contaminating particles, or even itself. This highlights the critical nature of producing and using graphene for ultrafast packaging and excessive mobility as well as the importance of grain size, substrate interference, and cleanliness.

2.2 Mxene: Mxene is a transition metal carbide, nitride, or carbon nitride (Fig. 2). There are six main Mxene structures that are extensively used in different fields. Solid solutions, such as (Ti, V)3C2, ordered in-plane double transition metal, mono transition metal Mxene, vacancies ordered, and vacancies randomly distributed are all examples of these structures (Singh et al., 2021).

3. SYNTHESIS

Separating atomic layers from layered compounds that exhibit strong layer-to-layer adhesion has been a major strategy for obtaining 2D materials since their discovery. The chemical bonds of two-dimensional materials are categorised according to their crystalline structure, and these materials may be either layered ionic solids, non-layered material, or Van der Wall solids (Mondal and Ghosh, 2019; Ronchi et al., 2019). Some principles were necessary for the synthesis of two-dimensional materials. That were essentially split into two schools of thought? Nanoscale materials may be grown and react into more complex materials using a bottom-up strategy, starting with atomic and molecule precursors. When working with big or bulky solids, the top-down method involves removing material from the top. This article compared and contrasted these two methods for producing graphene and Mxene.

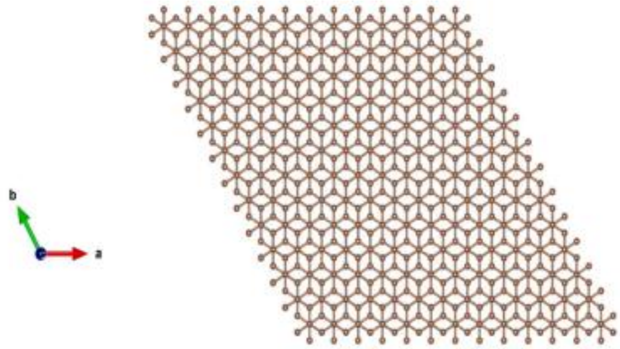

Figure 1: Figure show the close-up view of the structure of graphene which is an atomic-scale honeycomb lattice made of carbon atom.

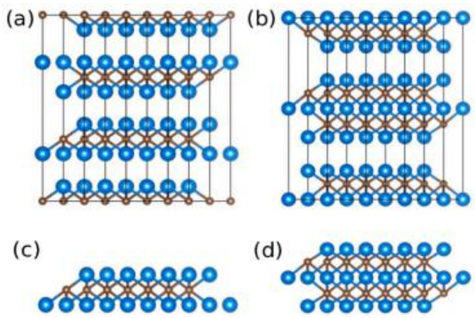

Figure 2: Side view of the structure of bulk phase and MXene of Ti 2 C (a, c) and Ti 3 C 2 (b, d)

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3.1 Synthesis of Graphene: Producing graphene in a controlled environment in order to achieve certain requirements for size, purity, and crystallinity. From graphite, graphene can be mechanically exfoliated (Sun et al., 2018; Novoselov et al., 2000); then, it can be chemically vapour deposited (CVD; Ritter and Lyding; Sutter et al., 2008; Dedkov et al., 2008; Reina et al., 2009; Jun et al., 2019); and finally, it can be reduced to graphene oxide by heating (Jun et al., 2019). Coraux et al. (2008), De Heer et al. (2010), and Hass et al. (2008) will cover the methods of CVD, mechanical exfoliation, and epitaxial growth on carbide for synthesising graphene.

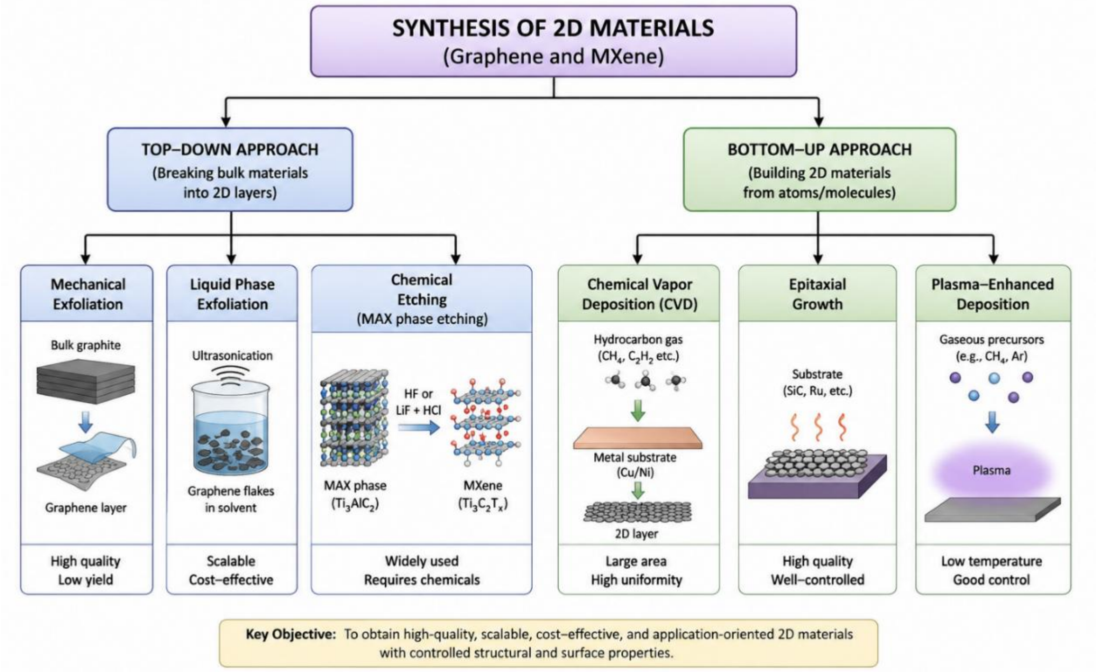

Figure 3: Overall Classification of Synthesis Techniques

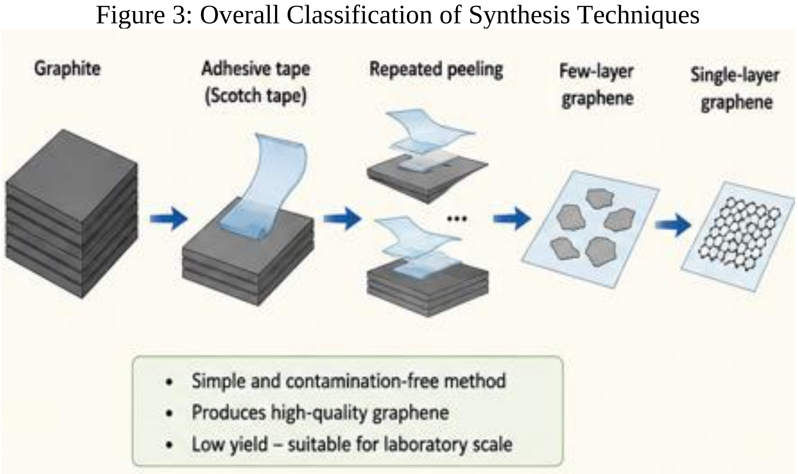

Figure 4: Mechanical Exfoliation

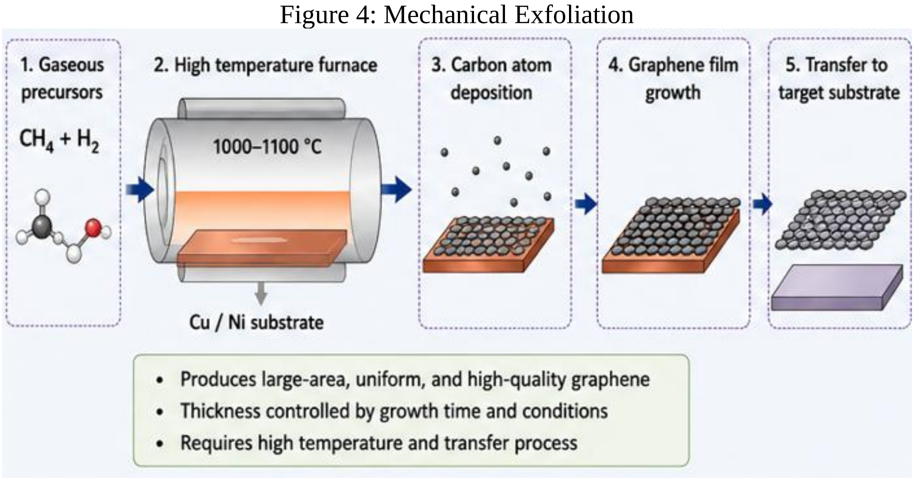

Figure 5: Chemical Vapor Deposition

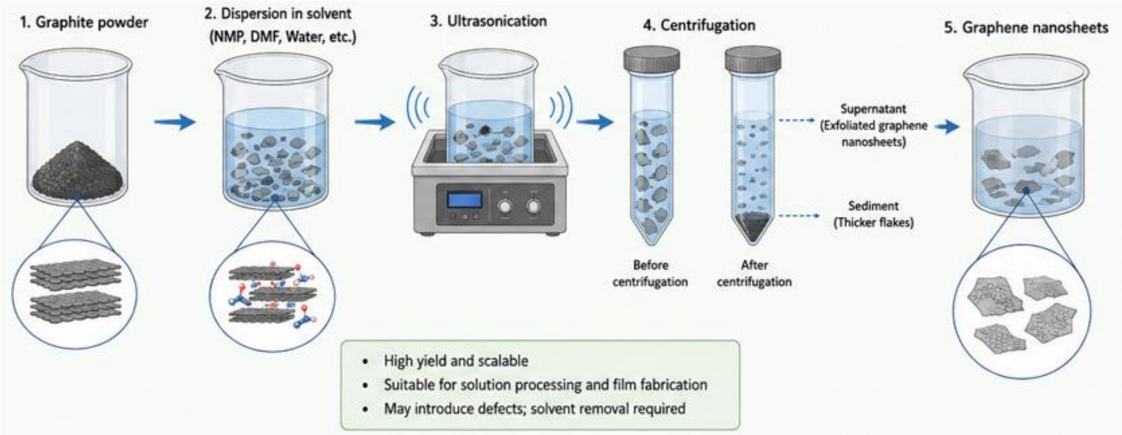

Figure 6: Liquid Phase Exfoliation

3.1.1. TOP-DOWN approach- While this method calls for a new approach to graphene manufacturing, we'll go over the two main techniques mechanical exfoliation and liquid exfoliation in this article. Because this device requires a quick and thorough production procedure in just a few minutes, mechanical exfoliation is an appealing approach for fabricating graphene. The "Scotchtape" technique is a mechanical exfoliant. Using this method, very pure graphite is reduced to a thin sheet of graphene. Scotch tape was used to separate the two pieces. Graphene, which has excellent electric conductivity, few crystal defects, and is formed from graphite by the direct exfoliation process, is of relatively high crystal quality. Even though the manufacturing yield is modest with this approach, graphene has real-world applications. This drawback causes the product to typically be contaminated with organic impurities.

In the top-down procedure, liquid-phase chemical exfoliation is another technique employed. Graphene is produced with a high yield using this approach. Oxidised graphite and graphite flakes made from powered graphite are produced in this high-quality. Graphene may be dispersed using a specific solvent at a concentration of 0.01 mg mt-1. Drop casting, vacuum filtering, and spray coating are the methods used to disperse the flakes.

The thicker fakes were removed by centrifuging the solution between 500 and 2000 rpm. However, graphene flakes piled from one to ten in the end. Because of the drawbacks of both methods—namely, poor graphene manufacturing quality and high impurity—we will be pursuing an alternative strategy.

3.1.2. BOTTOM-UP approach- Chemical vapour deposition (CVD) or epitaxial growth on SiC substrates are two methods that may be used in this strategy to synthesise graphene from tiny molecule carbon. The thickness may be regulated using the epitaxial approach by adjusting a number of rising factors and substrate catalysts. As a mass-production technology, CVD offers the greatest chance of producing high-purity graphene due to its huge area, excellent quality, and promising future. The bottom-up strategy and its technique will be covered in full presently.

3.1.2.1. Epitaxial growth on SiC substrates: Graphitisation of a silicon carbide wafer in a high-temperature ultra-high vacuum or atmospheric layer yields epitaxial graphene at high temperatures. Previous research by Rollings et al. (2006), Verger et al. (2019), and Li et al. (2021) has shown that the amount of a graphene layer on the SiC (001) may be adjusted by adjusting the growth parameter. The correlation between layer counts was also detailed. The authors speculated that, at low temperatures, prolonged sintering time is more effective than uncertain temperature increases in producing a consistent graphene layer, and that this effect grows with rising annealing temperature. Article reference (Verger et al., 2019) found, however, that micro-machine complexity, size, and cost are all negatively impacted by the bulk SiC substrate. The process of epitaxially growing a graphene layer on a silicon carbide wafer involves heating the wafer to the correct temperature to cause the sublimation of silicon and carbon. Graphene is created when carbon and silicon, which have been sublimated onto a SiC substrate, stay on the surface. According to Vazik et al. (2021), this is the process for synthesising graphene on a SiC wafer.

3.1.2.2. Chemical Vapor Deposition (CVD): CVD's end goal is to create a huge single crystal substrate for research into the escape process and potential commercial applications. We shall go into depth about CVD since it has many advantages over the other method, and because this procedure is also known as the bottom-up approach. A high-quality single-layered sheet may be produced across a vast area using this process, and it can be generated on both metal (copper) and insulator (silicon dioxide) covered silicon wafers. For the sample essay to be identified, the 300 nm thickness of the silica coating allows for good interaction between the Nano layer and the substrate. Upon depositing onto the substrate, the gaseous reactants solidify into a monolayer. Like non-reactive argon (Ar) with a low concentration of hydrogen gas, C H4 is used as a carrier gas in the CVD process.

Warming strong reactants (sugar and natural mixes, for instance organic examples) and using copper foil as a substrate allows for the utilisation of the strong source. Similar to how different regions of distorted precious stones grow into one another, this interaction has certain boundaries; deserts form at boundary intersections, which is almost the same as the grain in multi-crystalline materials.

3.2 Synthesis of Mxene

We will go over the structure of Mxene before getting into its production. In general, the Mxene is extracted from the MAX phase into the MnXn−1 layer by removing the interlayer A. (Naguib et al., 2012; Naguib et al., 2013) Here, A is an element of the IIIA and IVA group, M is an early transition element, and X may be carbide or nitride. The structure may be described as follows: X atoms in the MAX phase are positioned in the middle of the M octahedral cage that is shared by the edge, and M atoms are arranged in a hexagonal lattice.

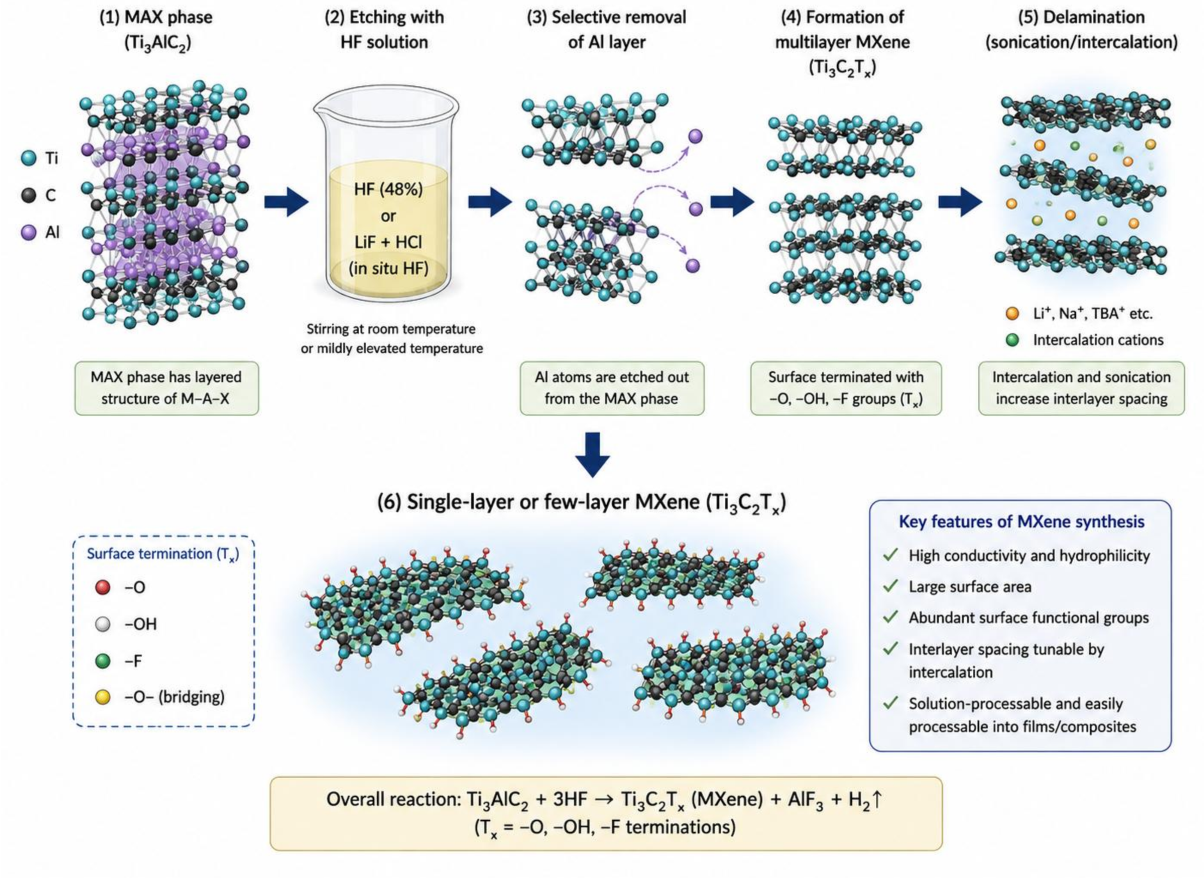

Figure 7: MXene Etching

3.2.1. The technique based on the top-down approach uses chemical etchants like HF acid and starts with a precursor derived from the MAX phase 3D structure (Stishenko and Kayumova, 2019; Mishra et al., 2016). Morphologically, this interaction calls for a large, erratic Mxene sheet that could be made with a side length of several hundred nanometres and thin sheets with a thickness of ten to twenty nanometres (Norimatsu and Kusunoki, 2009) Following union, the surface properties of the amalgam should be functionalised with -OH and -O according to this method. (The study conducted by Seok et al. in 2021)

3.2.2. Bottom-up approach: This process uses CVD, the self-templating method, or plasma-enhanced deposition to start with an atomic level and work its way up to a crystal growth of a Mxene layer of precursor. In this process, the carbon source keeps the gas flowing, which necessitates a temperature of about 1000 C. The morphology results in a multilayer film that is both highly crystalline and devoid of defects, with lateral sizes ranging from 10 to 100 µm. After synthesis, functional groups are absent from the surface characteristics. Naguib and colleagues were the first to employ aqueous hydrofluoric acid (HF) to replace Al atoms in Ti3AlC2 Mn+1Xn layers, in other words, Mxene, with surface (-O) or fluorine terminated (-F) atoms. A standard procedure for the production of Mxene has been put into action. Prior to the solid-liquid separation, the process's precursors were immersed in an etching solution, such as HF or acid-fluorides at an appropriate concentration, and the resulting mixture was then centrifuged or filtered. After that, it was rinsed with DI water (deionised water) until the pH level was brought down to 4 or 6. The solution was then subjected to shearing pressures or sonication in order to achieve a single-layered stack. The multilayered Mxene with its many functional groups (i.e. Tx) ended by a "A" layer stack. As seen in Figure 8, the interlayer gap is increased during the subsequent delamination process by introducing various cations, such as Li+, between the A-depleted multilayered Mxene.

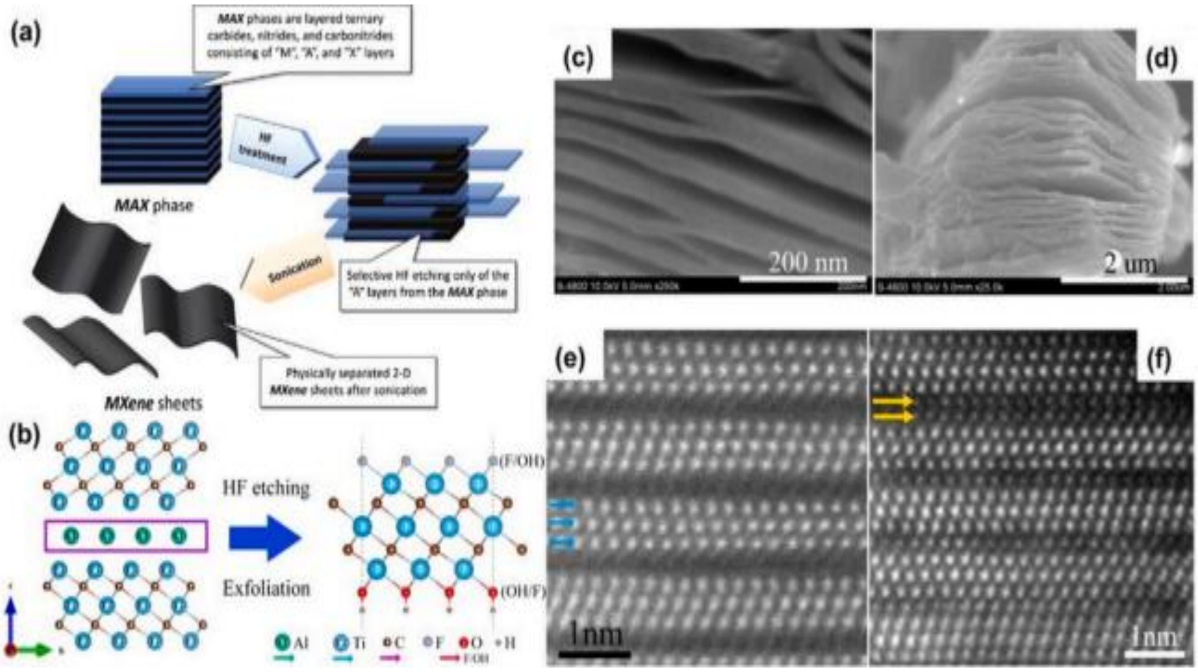

Figure 8: Diagram describing the synthesis process of Mxene from MAX phases. (b) Diagram illustration of the structural changes during Ti 3 c 2 X synthesis.

3.3 Recent Advances in Synthesis Techniques

The fast-paced development of graphene and MXene research has led to the emergence of new synthesis methods that focus on enhancing material quality, scaling up production, scalability, and environmental friendliness. While mechanical exfoliation, chemical vapor deposition (CVD), and hydrofluoric acid (HF) etching are still commonly used techniques, recent studies have been increasingly directed toward environmentally-friendly, fluoride-free and large-scale synthesis methods. Such novel techniques enable more precise control of the structural properties of these materials, including layer thickness, electrical characteristics, and surface functional groups, resulting in more desirable properties for sensing, energy storage, catalysis and biomedical applications.

Laser induced graphene (LIG) is an intriguing method, given that it can be used to turn polymer materials into porous graphene structures using laser irradiation without the use of catalysts or high vacuum systems, which is particularly appealing for graphene. The resulting material exhibits high surface area, excellent electrical conductivity and mechanical flexibility, especially for the applications of flexible gas sensors and wearable electronics (Lin et al., 2014; Paeng et al., 2024). Another method that has received a lot of attention is electrochemical exfoliation, as it allows for rapid production, is environmentally friendly and low-cost.

The electrochemical exfoliation process results in few structural defects and high-quality graphene sheets with excellent conductivity compared with conventional chemical oxidation processes. Moreover, plasma-enhanced chemical vapor deposition (PECVD) offers a low-temperature synthesis of graphene, which can be used with substrates that are easily damaged by high temperatures and flexible electronic devices.

For MXenes, however, the advances have been enormous by replacing the dangerous hydrofluoric acid etching method with safer approaches. Fluoride-free etching methods, molten salt etching and electrochemical etching have proven to be effective methods for producing high quality MXene nanosheets with low environmental hazards and better operational safety (Verger et al., 2019; Seok et al., 2021). The molten salt etching method has the advantages of good crystal morphology control, less structural damage, and the electrochemical etching method has the advantages of avoiding the direct use of concentrated acid, and better control of surface termination groups. Such research has recently focused on hydrothermal-assisted syntesis and template-assisted growth of porous and defect-engineered MXene with enhanced electrochemical activity and gas adsorption capability.

Recently, a few other trends have emerged: graphene and MXene have been hybridized with metal oxides, conducting polymers, quantum dots, and noble metal nanoparticles. These heterostructures show synergistic enhancements in charge transport, catalytic activity, mechanical strength, and gas adsorption properties. The hybrid materials have shown exceptional gass sensitivity and selectivity to NH_3, NO_2, H_2S, VOCs and further applications for environmental monitoring, healthcare diagnostics and flexible electronics (Pandey et al., 2024; Xia et al., 2023).

The key trends in recent syntheses are sustainable manufacturing, large scale production, defect engineering and precise surface functionalization. All these advances are projected to tip the pace of commercialization of graphene and MXene device applications in a wide range of engineering and biomedical applications.

Table 1: Comparison of Recent Synthesis Techniques for Graphene and MXene

Synthesis Technique	**Material**	**Principle**	**Major Advantages**	**Limitations**	**Representative Recent References**
Mechanical Exfoliation	Graphene	Peeling graphite layers	Highest crystal quality	Very low yield	Novoselov et al. (2004)
Liquid Phase Exfoliation	Graphene	Ultrasonication in solvent	Low cost, scalable	Sheet fragmentation, defects	Tian et al. (2018)
Chemical Vapor Deposition (CVD)	Graphene	Carbon deposition on metal substrate	Large-area, high-quality films	High temperature and expensive equipment	Gautam & Jayatissa (2011)
Laser-Induced Graphene (LIG)	Graphene	Laser irradiation of polymer	Flexible, porous, rapid fabrication	Limited thickness control	Lin et al. (2014); Paeng et al. (2024)
Electrochemical Exfoliation	Graphene	Electrochemical ion intercalation	Fast, eco-friendly, high conductivity	Electrolyte optimization required	Wang et al. (2020)
HF Chemical Etching	MXene	Removal of A-layer from MAX phase	High-quality MXene production	Hazardous chemicals	Naguib et al. (2012)
LiF–HCl Etching	MXene	In situ HF generation	Safer and controlled etching	Longer processing time	Verger et al. (2019)
Molten Salt Etching	MXene	High-temperature salt-assisted etching	Fluoride-free, high crystallinity	High processing temperature	Pandey et al. (2024)
Electrochemical Etching	MXene	Electrochemical removal of A-layer	Environmentally friendly, controllable	Lower production rate	Xia et al. (2023)
Hydrothermal-Assisted Synthesis	MXene Composites	Hydrothermal crystal growth	Enhanced porosity and surface activity	Longer reaction duration	Vaishag et al. (2024)

Table 2: Comparison between Top-Down and Bottom-Up Synthesis Approaches

Parameter	**Top-Down Approach**	**Bottom-Up Approach**
Basic Principle	Exfoliation or etching of bulk material	Atomic or molecular assembly
Typical Methods	Mechanical exfoliation, Liquid exfoliation, HF etching	CVD, PECVD, Epitaxial growth
Material Quality	Moderate to High	Very High
Structural Defects	Comparatively higher	Lower
Thickness Control	Moderate	Excellent
Scalability	Moderate	High
Production Cost	Lower	Higher
Equipment Requirement	Simple laboratory setup	Advanced instrumentation
Industrial Suitability	Medium-scale production	Large-scale commercial production
Typical Applications	Research, sensors, energy storage	Electronics, transparent electrodes, flexible devices

Over the last few years, the synthesis of graphene and MXenes has gone from the lab to sustainable, scalable and high performance fabrication processes. New techniques like laser induced graphene, electrochemical exfoliation, plasma enhanced chemical vapor deposition, molten salt etching, and electrochemical synthesis without the use of fluoride yield enhanced control of the structuring, and minimize environmental impact. Moreover, hybrid synthesis approaches combining graphene and MXene, with metal oxides, polymers and quantum dots have led to further improvements in the sensing performance, electrical conductivity, and catalytic activity. The progress of these advances suggest that future research will be directed toward the development of synthesis processes that are cost-efficient, environmentally-friendly, and industrially scalable, that can enable the commercialization of 2D materials in the following applications: flexible electronic devices, biomedical engineering, energy storage, and sensing.

In recent years, other environmentally friendly synthesis processes like electrochemical exfoliation, laser-induced graphene, fluoride-free MXene etching, molten salt etching, and plasma-assisted deposition have emerged as increasingly promising, due to their ability to cause fewer environmental hazards while producing excellent material quality. These sustainable synthesis routes are expected to be used in future for large scale industrial production.

4. APPLICATIONS

Today graphene and Mxene are the famous 2D material that are using in various application because of their various great properties like conductivity there hardness and many more. Here, this paper has discussed various applications like Bio-Medical, Sensor, Filtration, Energy storage.

4.1. Bio-medical: Mxene has some unique features such as high surface area, enhanced hydrophilicity, presence of functional groups, excellent mechanical and electronic characteristics, and biocompatibility which make it suitable for biomedical application (Xin et al., 2020) F. Wang et al. reported excellent biocompatible Tio 2 − Ti3C2 type of MXene material which is synthesized by hydrothermal process of synthesis and it was also used to develop a mediator free biosensor. This sensor can be implemented for a range of 0.1-380 μm (for H2O2). This type of biosensor is suitable for hemoglobin (Hb), in the detection of hydrogen peroxide and nitrite, Nafion is used (Wang et al., 2015) The fabricated device has shown excellent stability and reproducibility with a low range of measurement for glucose detection (Szuplewska et al., 2019) , (Nan et al., 2021) In Biomedical, the surface of Mxene can be reformed with various type of material (like biosensor, cancer theranostics) (Chand et al., 2022) Mxene can be used in biomedical and bio sensing application as it have some great properties like high surface area, superior hydrophilicity, the presence of functional group, great physicochemical, mechanical, electronic characteristics, high absorbance of electromagnetic radiation (NIF) region and biocompatibility (Dai et al., 2017) , (Wang et al., 2020) Xu et al. developed a sensor device in which semiconducting metallic characteristics of Ti3C2 MXene show low off-state leakage of current with appropriate bandgap.

When it comes to the first biomedical applications, graphene has showed a lot of promise for better medication delivery. The potential of graphene oxide as a cancer therapy and an anti-inflammatory medication has been the subject of much research. An immunosensor fabricated on a graphene surface has been developed for the detection of cancer biomarkers and alpha-fetoprotein (AFP). Because of its mechanical strength, graphene is well-suited for bone tissue and may one day be used to reinforce synthetic bone implants; it also promotes the formation of bone cells like osteoblasts. Citations: (Zhang et al., 2018), (George and Kandasubramanian, 2020). You can see graphene in action in the figure below, which illustrates its potential uses and situations where it excels above competing materials.

4.2. Energy storage: The defined layered structures and better electrical conductivity of Mxene have led to exceptional performances in energy storage devices. Using Mxene to enhance the performance of the superconductors in batteries allows them to attain high capacity and quick charged-discharge. Using an XRD characterisation approach that takes into account the solidification and defoliation mechanisms of V2CTx layers, D. Agnese et al. documented the electrochemical behaviour of 2D V2 C for Na-ion hybrid capacitors. It became the negative electrode once a complete cell was built with hard carbon within. According to Dalll'Agnese et al. (2015), after 100 cycles with a maximum cell voltage of 3.5V, it shows a capacitor of 50 mA hg− 1 at 6C. Graphene has a larger surface area than MXene. Concentrated acid-base treatment, which aids in inducing pores in the stiff Nano sheets of Mxene, may enhance this for advanced energy storage applications. These methods provide a variety of pseudo capacitive nanoparticles, which may enhance energy density, and they can accommodate the appropriate ions of high-voltage electrolytes. Source: Shen et al. (2012)

Fast charging and discharging in a short time period (ranging from 1 hour to 10 seconds) were shown by the results using composite materials in the production process. Many different kinds of batteries, including Li-ion batteries, might make use of graphene. Improved efficiency, stability, and charge-discharge cycle rates have been seen in graphene-based batteries. One way to store and retrieve charge is by using graphene, which has a high charge carrier mobility, a large surface area, and good conductivity (Wu et al., 2019).

Table 3: Summary on the application of Graphene.

Material	Substrate	Processing Technique	Application	Tested For
rGO	LCP	Vacuum Filtration	Biomedical	Structure Health Monitoring
Graphene	PDMS	CVD and Drop Casting	Biomedical	Artificial Skin
Graphene	Stretchable Yarns	Dip Coating	Biomedical	Human Motion Detection
Graphene	Polyester	Screen-printing	Energy Storage	Super Capacitor
Graphene	PET	Screen-printing and Drop-coating	Sensor	CO_2 Gas Detection

Graphene Oxide/rGO	Hydrogel Fibers	Space-confined Hydrothermal Synthesis	Energy Storage	Capacitive Energy Storage
Mesoporous Graphene	–	CVD	Energy Storage	Lithium-Ion Battery
Graphene	Si substrate	CVD and Transfer Method	Sensor	Resistance Temperature Sensor
Co_3O_4 Slices/rGO Hybrid	–	Mixing, Centrifugation and Annealing	Sensor	N_2O Gas Sensor

Table highlights the diverse applications of graphene across multiple fields due to its exceptional electrical conductivity, high mechanical strength, excellent thermal conductivity, and large surface area. The material is extensively utilized in sensors, energy storage devices, flexible electronics, biomedical engineering, environmental remediation, and composite materials. These applications demonstrate graphene's versatility and its significant contribution to the development of advanced nanotechnology-based devices.

Table 4: Summery on the application of MXene

Material	**Processing Technique**	**Tested For**	**Application**	**References**
MnO_x/Ti_3C_2 Composite MXene	Magnetic stirring and centrifugation	Cancer treatment	Biomedical	(Iqbal et al., 2019)
$Ti_3C_2T_x$ MXene	Ultrasonication	Anti-bacterial activity	Energy Storage	(Szuplewska et al., 2019)
PEG-modified Ti_3C_2	Etching and sonication	Anti-cancer modality	Biomedical	(Xiong et al., 2018)
Ti_4C_3 MXene	Etching and coating	Superconductor electrodes	Energy Storage	(Ren et al., 2016)
3D Porous MXene Form	Vacuum Filtration	Lithium-ion batteries	Energy Storage	(Sinopoli et al., 2019)
$Ti_3C_2T_x$	Centrifugation and Ball-milling	Superconductor	Sensor	(Champagne and Charlier, 2020)
MXene Textile Network	Dip-coating	Pressure sensor	Sensor	(Li et al., 2021)
3D MXene	Electrospinning	Volatile organic compound sensor	Sensor	(Wen et al., 2017)
$Ti_3C_2T_x$ MXene	Vacuum Filtration	Gas sensor	Sensor	(Kim et al., 2009)

Table presents the wide range of MXene applications, emphasizing its superior electrochemical properties, hydrophilicity, and abundant surface functional groups. MXenes are widely employed in supercapacitors, lithium-ion batteries, gas sensors, biosensors, electromagnetic interference shielding, water purification, catalysis, and biomedical systems. The table indicates that MXenes have emerged as highly promising materials for next-generation energy storage and sensing technologies.

4.3. Sensor: Wearable sensors based on Mxene are ideal because to its hydrophilicity, ease of use, and remarkable electrical and mechanical characteristics. Mxene has been used in the development of several sensor types, including gas sensors, electrochemical sensors, and many more. Several medical diagnostics, air pollution monitoring (at various locations), explosives detection, and chemical process control rely on gas sensors. Compared to other gas sensing methods, chemiresistive gas sensing is chosen due to its inexpensive cost and high performance (Xiong et al., 2018; Iqbal et al., 2019). Lee et al. detailed the first steps in making a Mxene gas sensor. In room temperature air, he measured the gas-detecting capabilities of Pt interdigital electrodes made on a flexible Polyimide base. Surface functionalisation with various terminal groups, such as -O, -OH, and -F, was found on Mxene. The sensor showed p-type semiconductor behaviour and increased resistance when exposed to ammonia, acetone, methanol, and ethanol gases. Acetone had the lowest sensitivity and ammonia the greatest, with a limit of detection of 9.27 ppm, according to the results.

Wearable electronics for sports, electronic skin, and health care monitoring have integrated graphene-based flexible strain sensors (Zhu et al., 2014; Aghaei et al., 2021). These sensors may detect vital signs such as heart rate, blood sugar, blood pressure, electrocardiogram (ECG) and electromyogram (EMG) signals, core body temperature, and more in real-time. When it comes to flexible electronic sensors, graphene's distinctive chemical and physical qualities are a major selling point. Graphene is used in gas and chemical sensors to detect a range of gases, including ammonia (NH3), carbon dioxide (CO2), sulphur dioxide (SO2), nitrogen dioxide (NO2), hydrogen (H2), hydrogen sulphide (H2S), and several volatile organic compounds (VOCs).

4.4. Filtration: Membranes with a high flux, excellent stability, and resistance to dirt and chlorine chemicals are required for sewage treatment and desalination (Singh et al., 2017). The thinness and mechanical stability of a membrane allow it to maximise water permeability while minimising salt rejection ratio. Graphene and graphene oxide based membranes were previously utilised for sieving purposes; however, the interlayer spacing in these materials becomes relatively small when subjected to pressure, which is why Mxene, with its adjustable surface chemistry and controllable layer spacing, has proven to be an incredibly practical material. In their groundbreaking work, Ren et al. brought attention to the first Mxene-based membrane. They achieved this by assembling nanometer-thin sheets of 2D Ti3C2Tx(MXene) into either a freestanding or supported membrane, which enables charge-and-size selective rejection of ions and molecules. By filtering a colloidal solution of delaminated Ti3C2Tx(MXene), a membrane with controllable mass-loading and thickness was produced using vacuum-assisted filtration (VAF). This membrane exhibited high selectivity towards dye cations of varying sizes as well as single-, double-, and triple-charged metal cations. When it comes to the separation of cations with greater charges, the Ti3C2Tx(MXene) Membrane outperforms GO (Goh and Ismail, 2018). The electrical devices made from graphene and Mxene are shown in Table 3. Research on Mxene devices is ongoing since, as a result of their low resistive contact, none have been found so far. Gas sensors, strain gauges, and other energy storage devices often use methylxene. The business, however, has not implemented it just yet.

Table 5: List of electronic device produced with Graphene and Mxene

Graphene Device	MXene Device
IBM Transistor – 26 GHz (Marriwala, 2022), (Marriwala et al., 2016)	Low resistive contact
Samsung Transistor – 94 GHz to THz	–

Table compares the electronic devices developed using graphene and MXene materials. Both materials are extensively applied in flexible sensors, wearable electronics, transparent electrodes, supercapacitors, batteries, transistors, and smart electronic systems. The comparison shows that graphene is preferred for applications requiring high electrical conductivity and flexibility, whereas MXenes are more suitable for electrochemical devices due to their excellent ion transport capability and surface reactivity. Together, these materials play a vital role in advancing modern electronic technologies.

5. CONCLUSION

Graphene and MXenes are two of the most promising two-dimensional materials for future technologies because of their exceptional mechanical, electrical, chemical, and physical properties. This paper shows that graphene is great for transparent conductive coatings, high-performance sensors, and flexible electronics because of its structural stability, mechanical flexibility, and outstanding electrical conductivity. Xenes, on the other hand, are highly effective in energy storage, biosensors, electromagnetic shielding, catalysis, and environmental remediation due to their superior hydrophilicity, abundance of surface functional groups, high electrochemical activity, and excellent ion transport capabilities. When combined, the two materials' complementing qualities and distinct strengths make them ideal candidates for use in hybrid nanocomposites, which have the potential to vastly improve device performance. Promising developments have not yet led to broad commercialisation due to issues with large-scale synthesis, oxidation stability, manufacturing cost, and operating dependability over the long term. Building multifunctional graphene-MXene hybrid systems for advanced sensing, biomedical, environmental, and energy applications; improving material stability through surface engineering and functionalisation; and developing scalable and environmentally friendly fabrication techniques should be the focus of future research. Faster practical use of these sophisticated 2D materials in many industrial and healthcare areas is anticipated as a result of ongoing multidisciplinary research.

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