MXENE GRAPHENE COMPOSITES AS A POTENTIAL MATERIAL IN DIVERSE FIELD

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Abstract

MXene-graphene composites have drawn attention due to their remarkable properties and potential applications in various fields. This systematic study aims to comprehensively review the current situation of MXene-graphene composite materials by examining their synthesis methods, structural characteristics, and functional aspects. The paper explores a range of uses for these composites, such as electrical devices, biological applications, energy storage, and environmental remediation. The report discusses the obstacles and future objectives in this quickly developing field while highlighting material performance gains by analyzing the synergistic impact of mixing MXenes with graphene. This study highlights the importance that MXene-graphene composites play in developing next-generation materials and technologies and provides insights into the potential of these materials to transform several industries through a critical evaluation of recent studies.

Keywords: MAX, Graphene oxide (GO), Mxene/Graphene, Reduced graphene oxide(rGO).

Introduction

The field of materials sciences has seen unpredictable advancements in recent years, with MXene emerging as a prominent and promising material. Discovered by researchers at Drexel University in 2011, MXenes are two-dimensional materials that are derived from MAX phases.[1][2]. These materials are prepared by etching the A layer in the presence of strong etching agents like hydrofluoric acid (HF) or a mixture of strong acids and fluoride salts. MXene originating from the MAX phase is prepared by the etching of A layer in the presence of strong etching agents like HF (see figure 1) or a mixture of strong acid and fluoride salts and denoted by
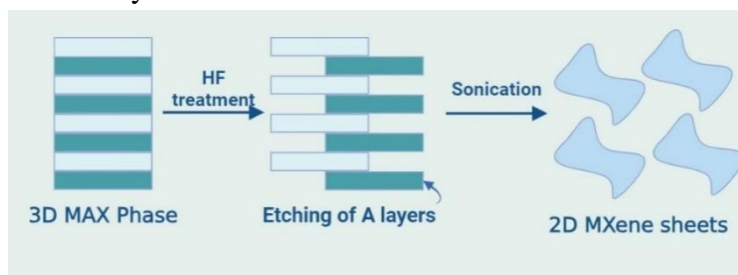
Figure 1. Etching of A layer From MAX phase [3]

$M_{n+1}AX_n$ where M refers to a transition metal, A to the elements of boron or carbon family, X is C or N and n can be 1,2 or 3[4][5][6]. MXenes, with the formula $M_{n+1}X_nT_x$, where T represents surface functional groups such as –O, −OH, and –F[7], have a wide range of applications, including solar fuel generation[8], water splitting[9], photocatalysis[10][11], hydrogen evolution[12][13], CO_2 reduction[14][15], nitrogen fixation[16], pharmaceutical mitigation, and pollutant degradation. The interweaving of MXenes with other materials, such as graphene and graphitic carbon nitride, has further expanded their application in various fields of chemistry potential, mostly in advanced electrocatalytic hydrogen evolution, showing highly exceptional performances. Graphene, on the other hand, was discovered by Researchers Andre Geim and Konstantin Novoselov in 2004 at the University of Manchester[17] using the method of, mechanical exfoliation also known as the scotch tape method. [18] Graphene has special chemical reactivity amongst foreign materials in comparison to other bulk carbon allotropes due to which it is not replaceable by carbon nanotubes and fullerenes. This two-dimensional material consists of sp^2 hybridizedcarbon atoms[19] in a hexagonal manner i.e. hexagonal lattice, has unique properties such as energy storage devices[20],green energy applications[21], dye-sensitized solar cells[22]etc. attracted the researcher's attention in various fields of research. Graphene materials have strong electrical and thermal conductivity, high mechanical strength, and large surface areas having 1TPAYoung's module value.The discovery of graphene marked a significant milestone in science. Geim and Novoselov got the Nobel Prize in Physics in 2010 for their discovery.

The synthesis of MXene-graphene composites came into existence after the tremendous applications of MXene, as well as graphene researchers, thought about combining two strong materials to develop an extraordinary material thatcombines the advantageous properties of both materials, resulting in composites with enhanced properties and a broad range of applications. These include biosensors (glucose bio sensing)[23], drug delivery systems, PPE development[24], implant coatings, supercapacitors [25][26], stretchable supercapacitors[27], batteries[28][29], fuel cells, flexible electronics[30], and wearable strain sensors[31]. The designed MXene-graphene hybrids have shown promising applications as flexible supercapacitors, electrodes, ion batteries, and EMI-shielding materials. Despite their potential, the application of MXene-graphene composites in biomedical fields such as drug delivery, and cancer therapy faces challenges related to biocompatibility, toxicity, and clinical assessment. Furthermore, the limitations of graphene oxide (GO) membranes in aqueous applications, such as instability and low permeability, represent significant obstacles to their broader use in water treatment.

This systematic review aims to provide a detailed examination of the synthesis, properties, and applications of MXene-graphene composites, offering insights into their potential to revolutionize various industries and contribute to the advancement of next-generation materials and technologies. Through a critical analysis of recent research, the review will highlight the progress, challenges, and future directions in this dynamic field. Various methods have been used to create MXene/graphene composites, including mechanical mixing, self-assembly, hydrothermal techniques, heat treatment, and reagent reduction. Among these, hydrothermal techniques are commonly used.

For example, MXene ($Ti_3C_2T_x$)/reduced graphene oxide structures were created at low temperatures (65 °C) and then underwent a freeze-drying process. Ascorbic acid was used in the hydrothermal reaction to prevent the MXene structures from oxidizing.

Preparation

Electrostatic self-assembly process

MXene/rGO hybrid electrode films were prepared via an electrostatic self-assembly method. Initially, a suspension of graphene-PDDA (G-PDDA) was slowly added dropwise into 20 mL of MXene suspension (with a concentration of 0.5 mg mL^{-1}) under stirring. Following this, the mixture underwent probe sonication for 10 minutes to ensure thorough mixing. Subsequently, the mixture was filtered using a polypropylene membrane with abundant deionized water and then dried in a vacuum hood for 12 hours to obtain flexible and freestanding MXene/rGO films. These films were denoted as M/G-x, where 'x' represents the mass ratio of rGO in the hybrid. Different mass ratios, such as M/G-1%, M/G-5%, and M/G-10%, were achieved by altering the volume of the G-PDDA suspension (0.2 mL, 1 mL, and 2.2 mL, respectively)(see Figure 2). For comparison, a pure MXene film was also prepared without the incorporation of rGO. Material characterizations were conducted to analyze the morphology, crystal structure, chemical composition, surface charge, electrical conductivity, film thickness, and surface area of MXene and MXene/rGO hybrid samples. Scanning electron microscopy (SEM) and Transmission electron microscopy (TEM) were utilized to observe morphology, while X-ray diffraction (XRD) patterns were measured to assess crystal structure. Raman spectra were recorded using a confocal spectrometer, and chemical compositions were analyzed via high-resolution X-ray photoelectron spectroscopy (XPS) with peak fitting. Zeta potential measurements were performed using a Zetasizer, and electrical conductivity was measured with a four-point probe instrument. Film thickness was determined using a high-accuracy micrometer, and nitrogen adsorption-desorption isotherms were measured with a gas adsorption analyzer. These comprehensive analyses provided insights into the structural and functional properties of the materials, essential for understanding their potential applications [26][32].
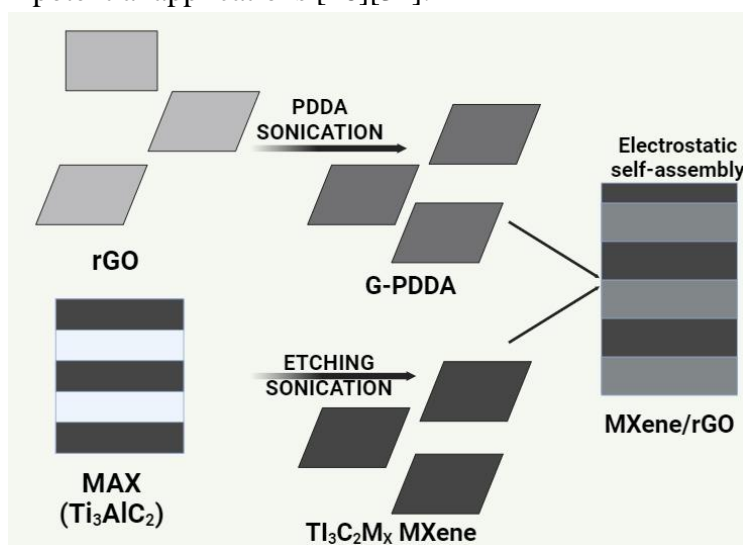
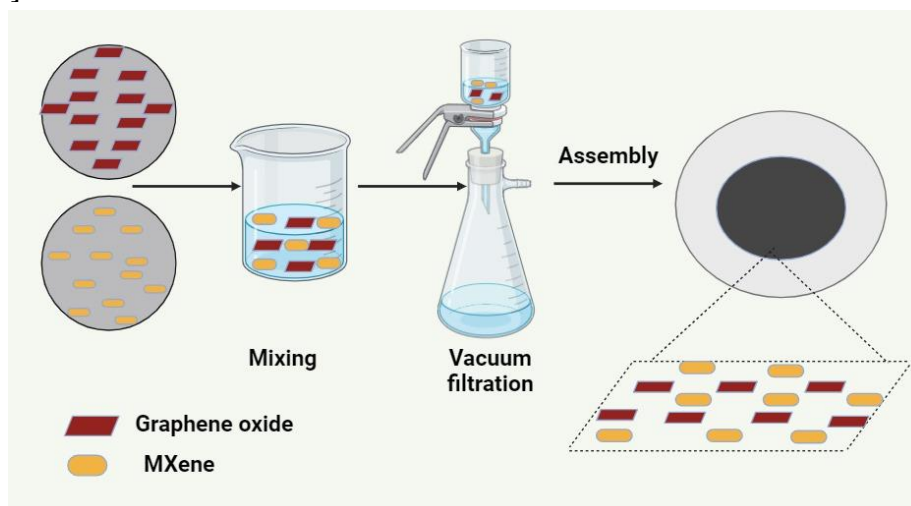**Figure 2.** Diagram showing the preparation of MXene/rGOhybrid by self-assembly method [32]

Mechanical mixing

The production of MXene-rGO aerogel-based MSC involves several steps and chemicals. At first, a mixture of Al, C, and TiH_2 powders in a molar ratio of 3:1.1:2 is ball-milled for 18 hours and then heated to 1400°C under an Ar atmosphere for 2 hours to form the MAX phase precursor ($Ti_3C_2T_x$). For MXene($Ti_3C_2T_x$) nanosheet dispersion, hydrochloric acid, LiF powder, and the MAX phase precursor are used. The process involves adding water to hydrochloric acid to prepare 9 M HCl, slowly adding LiF powder to the HCl solution, and then adding the MAX phase precursor followed by magnetic stirring for 24 hours at 35°C. This mixture undergoes centrifugation, sonication, and further centrifugation to obtain the $Ti_3C_2T_X$ nanosheet dispersion. Additionally, a modified Hummers method is used to produce graphene oxide (GO). In the production of MXene-rGO aerogel-based MSC, the GO solution is mixed with the MXene solution and sonicated to achieve uniformity. Various ratios of GO to MXene are tested, and the mixture is freeze-dried to form an aerogel. The aerogel goes through immersion in a mixture of hydroiodic acid (HI) and acetic acid (HAc) and is then washed with ethanol and water. Finally, the aerogel is patterned using laser processing, wrapped with a gel electrolyte of PVA-H_2SO_4, and vacuum dried. Self-repairing PU from Wanhua Chemical Group Co., Ltd. is applied to enhance durability. In addition to the production steps and chemicals used, various characterization techniques are employed to assess the properties of the MXene-rGO aerogel-based MSC. Scanning electron microscopy (SEM) with an energy-dispersive X-ray spectroscopy (EDS) system is used to investigate the structure and morphology of the MXene-rGO aerogel and the MXene nanosheets. Transmission electron microscopy (TEM) with an EDS system provides further insight into the nanoscale structure. X-ray diffraction (XRD) analysis is performed to determine the crystallographic structure of the materials. X-ray photoelectron spectroscopy (XPS) is employed to investigate the elemental composition and chemical states of the samples. Additionally, the size distribution of graphene oxide (GO) and MXene nanosheets is determined using a particle size analyzer (Nano-ZEN 3600, Malvern Instruments, UK). These characterization techniques offer comprehensive information about the composition, structure, and morphology of the MXene-rGO aerogel-based MSC, ensuring its suitability for various applications[33][34][35][36].

Filtration method

To synthesize the GO/MXene composite membranes, a mixed cellulose ester (MCE) membrane with a pore size of 0.45 μm was chosen as the supporting layer. The fabrication process involved the following steps: Preparation of Suspension in whichAn aqueous suspension containing a total mass of 1 mg of GO and MXene was mixed with 100 mL of deionized (DI) water. Ultrasonic Dispersion in whichThe mixture was subjected to ultrasonic vibration for 5 minutes to ensure thorough dispersion. Stirring and Mixing the solutions of GO and MXene were meticulously stirred and ultrasonically mixed to achieve uniformity. Membrane Formation in which GO/MXene composite membranes were prepared using varying mass ratios of GO to MXene, including 1/0, 4/1, 2/1, 1/1, 1/2, 1/4, and 0/1, to tailor the properties according to specific requirements. (see figure 3) Several techniques were employed to evaluate the physical and chemical properties of the GO and MXene nanosheets and the structure of the GO/MXene composite membranes:

Atomic Force Microscopy (AFM) was used to determine the thickness of the nanosheets. X-ray Diffraction (XRD) explores the interlayer spacing of the composite membranes. Scanning Electron Microscopy (SEM) provided surface and cross-section images of the membrane microstructure. X-ray Photoelectron Spectroscopy (XPS) analyses the relative elemental composition—Fourier Transform Infrared Spectroscopy (FT-IRinvestigates the content of oxygen-containing functional groups. Surface Contact Angle Measurement Characterizes the hydrophilicity of the composite membranes. UV-visible absorption Spectroscopy determines the concentrations of organic dye molecules and humic acid in the permeate. Size Exclusion Chromatography (SEC) measures the molecular weight distribution of bovine serum albumin[37].


Figure 3. Diagram showing the preparation of Rgo/Mxene composites by filtration method [37]

MXene – Graphene hybrid fibres for nh3 gas sensing

Sang Hoon Lee and co-workers Studied MXene/Graphene hybrid fibers and their extraordinary property of exhibiting heightened NH_3 gas sensitivity at room temperature, with a notable improvement ($\Delta R/R0 = 6.77\%$) compared to individual MXene and graphene components. The fibers maintain exceptional mechanical flexibility and low noise resistance even after 2000 bending cycles, enabling gas sensing during deformation. Mxene/Graphene hybrid fibers are so flexible that they are woven into a lab coat in a practical application, showcasing their potential for integration into wearable devices.The enhanced NH_3 sensing performance, attributed to the optimized band gap, synergistic effects, and increased oxygen in the MXene terminal atom, comes with low power consumption. The flexible structure, featuring a wrinkled surface and small pores, proves resilient in bending fatigue tests. The minimal noise induced by deformation ($\Delta R/R0 = \pm 0.2\%$) compared to the gas response makes these fibers suitable for wearable devices.The process begins with mixing MXene and graphene oxide (GO) in water at a concentration of 10 mg/mL, where GO acts as the matrix for the fibers. This mixture undergoes a solvent exchange process, transitioning from water to N,N-Dimethylformamide (DMF) through centrifugation. The MXene/GO dispersion is then subjected to a solvent exchange with DMF in a 1:7 volume ratio. Next, the resulting mixture is extruded into a coagulation bath containing a 5:5 vol.% mixture of n-hexane and dichloromethane.

This combination leads to the formation of gel-like fibers, driven by the solubility parameter difference between the coagulation solution and the MXene/GO-DMF mixture. These gel fibers are collected and air-dried naturally under ambient conditions. (see figure 4) To enhance their properties, the dried fibers undergo thermal reduction at 200 degrees Celsius in an inert gas environment, resulting in the production of MXene/reduced graphene oxide (rGO) hybrid fibers with improved characteristics suitable for various applications.
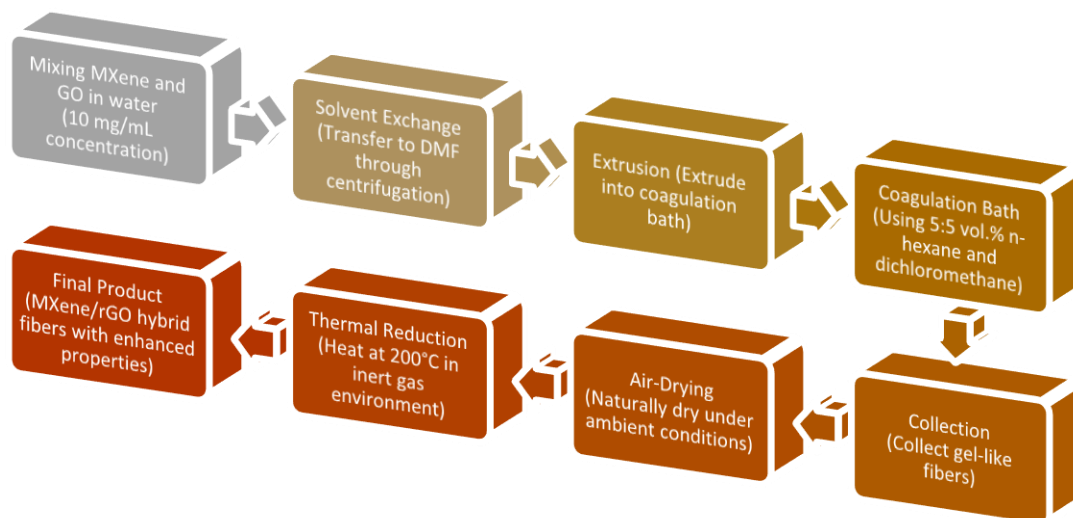
Figure 4. Preparation of MXene/rGO hybrid Fibers for NH_3 gas sensing with enhanced properties via solvent exchange method

 In the gas sensing experiment, the change in resistance of the MXene/rGO hybrid Fiber is measured. Copper tape is used to create electrodes at both ends of a glass substrate, with the MXene/rGOfiber placed between them and secured in place. The setup is then enclosed in a sealed chamber, with the copper electrodes connected to alligator clips. To stabilize the fiber's resistance, the chamber is initially filled with nitrogen gas. Subsequently, the target gas is introduced into the chamber, diluted with nitrogen gas as required, and the gas flow is regulated using a mass flow controller. As the target gas interacts with the MXene/rGOfiber, it induces a change in the fiber's resistance. This change in resistance is monitored in real-time using a digital multimeter, allowing for the analysis of how the fiber responds to the presence of different gases, facilitating gas sensing[38].

Water purification

GO/MXene composite membranes are used for water purification through a filtration process. These membranes are made by combining graphene oxide (GO) and MXene nanosheets into a supporting layer, usually a mixed cellulose ester (MCE) membrane. The membranes are designed to allow water molecules to pass through selectively while effectively removing organic contaminants from water. Water containing contaminants is passed through the GO/MXene composite membrane using pressure or vacuum filtration methods. The addition of MXene to the GO membrane enhances the space between GO nanosheets, reducing resistance to water flow. This leads to increased water permeability through the membrane.

The structure and properties of the composite membrane enable it to selectively reject organic contaminants present in water. Size exclusion and electrostatic interactions between the membrane and contaminants contribute to their removal. The GO/MXene composite membranes have high rejection rates for various contaminants, including dyes, and high molecular weight organic substances such as humic acid (HA) and bovine serum albumin (BSA). This high removal efficiency ensures the purity of the treated water. Moreover, the composite membranes demonstrate structural stability and reliability in aqueous conditions, making them suitable for long-term water purification applications. Overall, GO/MXene composite membranes offer an effective and efficient solution for water purification, providing high flux, selective removal of contaminants, and stability, thereby contributing to a clean and safe water supply[39].

Transport properties of a highly conductive 2D Ti_3C_2Tx MXene/graphene composite
The research focuses on creating and analyzing a composite material made of MXene (specifically Ti_3C_2Tx) and graphene. This composite is produced using an alternating electrospray technique, which deposits MXene and graphene materials layer by layer. The study systematically examines the structural and electrical properties of the composite, particularly about changes in graphene content. The results showed that incorporating graphene into the composite significantly reduced surface roughness. Electrical measurements indicated a consistent increase in electrical conductance and Hall carrier mobility as the concentration of graphene increased. Notably, even at a low concentration of 2.5 wt.% of graphene, the composite displayed remarkably high electrical conductance and Hall carrier mobility values. These findings suggest that the composite possesses excellent electrical properties, potentially making it one of the most electrically conductive MXene-based composites known to date. The research findings underscore the potential of this MXene/graphene composite for various applications in thin-film electronics[40].

The process of preparing MXene/graphene layers involved several steps. Initially, multilayer Ti_3C_2Tx particles were created by treating Ti_3AlC_2 particles in a 50 wt.% aqueous HF solution to remove aluminum, resulting in delaminated Ti_3C_2Tx particles. These particles were then dispersed in ethanol through probe sonication and subsequent centrifugation. At the same time, a solution of pristine defect-free graphene nanoplatelets was prepared with an initial concentration of 0.05 mg/ml. Both the Ti_3C_2Tx dispersion and graphene solution were utilized in different proportions. Alternating deposition of Ti_3C_2Tx and graphene layers onto a glass substrate was achieved using an electrohydrodynamic atomization (EHDA) deposition technique. Varying potentials were applied to observe different modes of electrohydrodynamic atomization for Ti_3C_2Tx and graphene flake dispersions. Specifically, a stable cone-jet mode was employed to obtain Ti_3C_2Tx/graphene composite thin films. This process involved rinsing the substrate with ethanol, drying, and adjusting the stand-off distance to achieve the desired coverage area. Alternate deposition was repeated to create composite films comprising 5–10 alternating layers of Ti_3C_2Tx and graphene. Finally, the composite film was annealed under a vacuum at 200°C for 2 hours (see Figure5) [40].
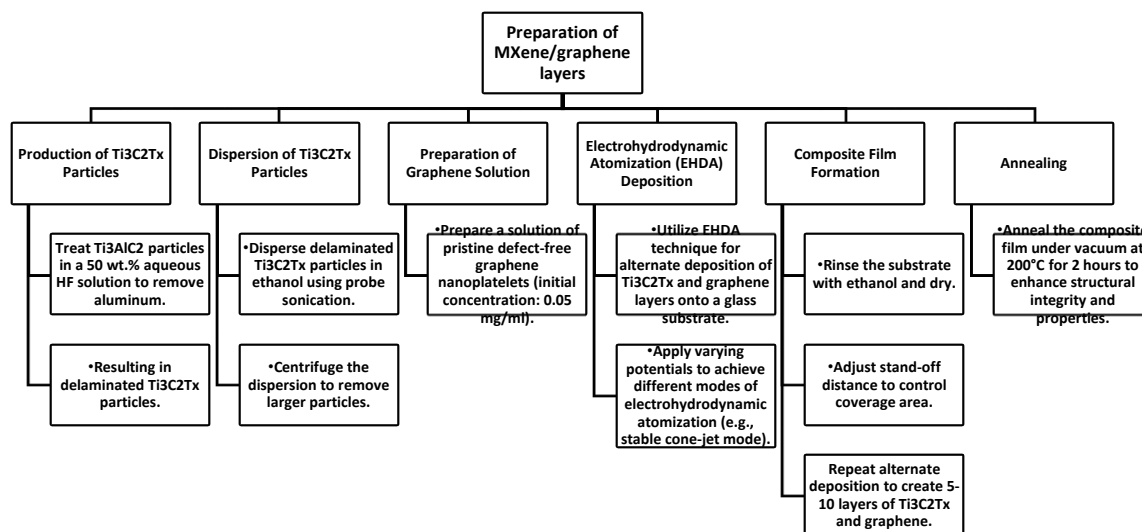
Figure 5. Flowchart outlining a myriad of techniques for the preparation of advanced Mxene/graphene layers

A lightweight and conductive MXene/graphene hybrid foam for superior electromagnetic interference shielding

In this study, a novel strategy was developed to enhance the electrical conductivity of three-dimensional (3D) graphene, addressing its limitations for effective electromagnetic interference (EMI) shielding due to its inferior conductivity. This was achieved by incorporating highly conductive two-dimensional Ti_3C_2Tx MXene nanosheets into graphene oxide (GO) to fabricate a lightweight MXene/graphene hybrid foam (MX-rGO) with improved electrical conductivity. The interconnected porous structure of the foam facilitates efficient wave attenuation, resulting in an outstanding EMI shielding effectiveness of 50.7 dB. Moreover, the specific EMI shielding effectiveness (SSE), which considers the shielding effectiveness relative to material density, reaches up to 6217 cm3 g^{-1} at a lower thickness, surpassing most reported EMI shielding materials. The synthesis process involved mixing concentrated Ti_3C_2Tx MXene and GO dispersions at different mass ratios (0:1, 1:1, 1:2, and 1:3), followed by 20 minutes of magnetic stirring and ultrasonic dispersion. The resulting uniformly mixed colloidal solution was then loaded into a plastic MD and frozen at -18 °C before undergoing vacuum freeze-drying at -65 °C and 25 Pa to produce lightweight MX-GO hybrid foam. Subsequently, the hybrid foams were calcined and heat-treated for 1 hour at 300 °C under Ar gas protection.

The resulting MX-rGO hybrid foams demonstrated remarkable electrical conductivity, reaching 1000 S m^{-1}, with the MX-rGO1:1 variant achieving an exceptional conductivity of 1250 S m^{-1}. However, conductivity decreased with increasing GO content, as observed in MX-rGO1:2 (1000 S m^{-1}) and MX-rGO1:3 (303 S m^{-1}). The MX-rGO foam exhibited a high EMI shielding effectiveness of 50.7 dB, with an ultrahigh specific EMI shielding effectiveness (SSE) of 6217 cm^3 g^{-1} at lower thicknesses, demonstrating its potential for aerospace and smart device applications.This study highlights the promising capabilities of MXene/graphene hybrids in providing lightweight and highly effective EMI shielding solutions for electromagnetic wave interference[41].

Flexible MXene/Graphene Films for Ultrafast Supercapacitors with Outstanding Volumetric Capacitance

The strategy presented involves the electrostatic self-assembly of positively charged reduced graphene oxide (rGO) modified with poly(diallyl dimethylammonium chloride) and negatively charged titanium carbide MXene nanosheets to prepare flexible and conductive MXene/graphene supercapacitor electrodes. This process effectively prevents the self-restacking of MXene nanosheets and increases interlayer spacing, allowing for accelerated diffusion of electrolyte ions and enhanced accessibility of electroactive sites. The resulting MXene/rGO-5 wt% electrode exhibits a volumetric capacitance of 1040 F cm^{-3} at a scan rate of 2 mV s^{-1}, impressive rate capability with 61% capacitance retention at 1 V s^{-1}, and long cycle life. Additionally, the binder-free symmetric supercapacitor demonstrates an ultrahigh volumetric energy density of 32.6 Wh L^{-1}, among the highest reported for carbon and MXene-based materials in aqueous electrolytes. This work offers fundamental insights into the influence of interlayer spacing on the electrochemical performance of 2D hybrid materials, for the design of next-generation flexible, portable, and highly integrated supercapacitors with superior volumetric and rate performances. The fabrication process of flexible MXene/rGO hybrid films involved the preparation of rGO nanosheets through hydrazine reduction of GO, followed by dispersion in a poly(diallyl dimethylammonium chloride) (PDDA) solution using probe sonication to achieve a suspension with a concentration of 0.5 mg mL^{-1}. MXene/rGO hybrid electrode films were then prepared via an electrostatic self-assembly process. In this process, the G-PDDA suspension was added drop by drop into 20 mL of MXene suspension (0.5 mg mL^{-1}) under stirring, followed by probe sonication for 10 minutes. The resulting mixture was filtered using a polypropylene membrane with copious deionized water and then dried in a vacuum hood for 12 hours to obtain flexible and freestanding MXene/rGO films, denoted as M/G-x, where x represents the mass ratio of rGO in the hybrid. Different mass ratios of rGO in the hybrid, specifically M/G-1%, M/G-5%, and M/G-10%, were achieved by adjusting the volume of the G-PDDA suspension to 0.2, 1, and 2.2 mL, respectively. For comparison, a pure MXene film was prepared without the presence of rGO (see Figure 6) [42].
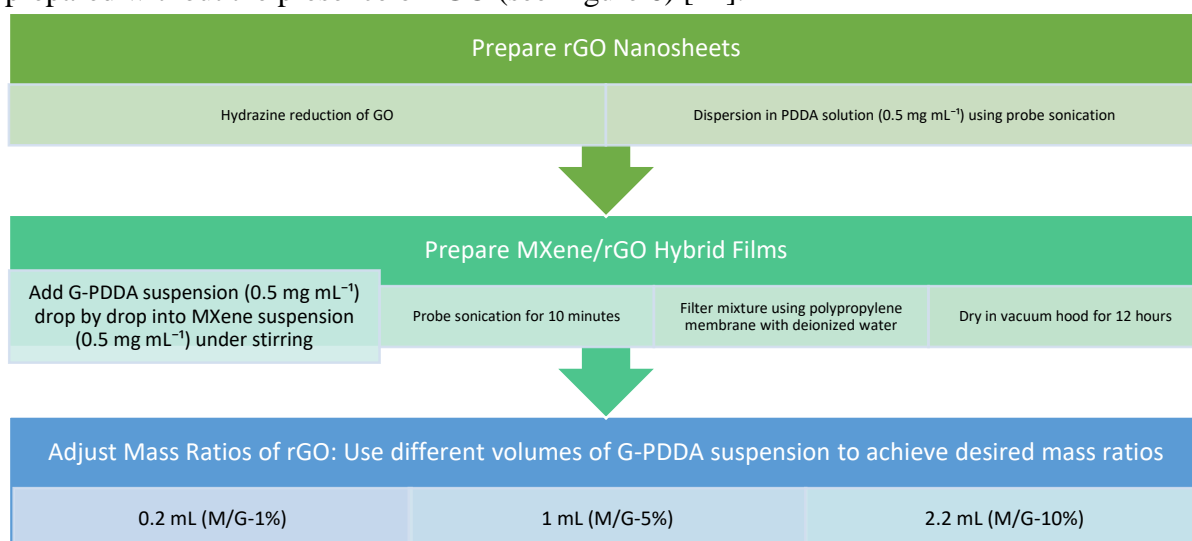
Figure 6. Preparation of Mxene/rGO hybrid film suspension for ultrafast supercapacitors with outstanding volumetric capacitance

MXene/Graphene Heterostructures as High-Performance Electrodes for Li-Ion Batteries

In recent years, there has been a significant advancement in the development of MXene/graphene heterostructures as high-performance electrodes for Li-ion batteries, owing to their remarkable electrochemical properties. To gain a deeper understanding of the mechanisms underlying their promising experimental results, a systematic investigation was conducted using first-principles calculations, focusing on Ti_2CX_2 (X = F, O, and OH) as representative MXenes. These calculations revealed several key insights into the behavior of MXene/graphene heterostructures. Firstly, the integration of graphene into MXene effectively mitigates the restacking effects of MXene layers, which is crucial for enhancing the overall performance of the electrode material. This ensures that more electroactive sites remain engaged, which facilitates rapid ion transport, contributing to swiftdischarging and charging processes utilizing the characteristics of high-performance Li-ion batteries. Additionally, the interaction of graphene enhances the electrical conductivity of the heterostructures, by improving the efficiency of charge transfer within the electrode material. The presence of graphene strengthens the Li adsorption strength at the interface and still maintains high Li mobility, which is essential for achieving high specific capacities and long-term stability in Li-ion batteries. The mechanical stiffness of the heterostructure is substantially enhanced, ensuring structural stability during lithiation and contributing to the overall durability of the electrode material. Among the studied materials, the Ti_2CO_2/graphene heterostructure emerged as the most promising candidate, exhibiting superior electrochemical performance compared to other MXene/graphene heterostructures. These findings provide valuable insights into the rational design of MXene-based electrodes for Li-ion batteries, paving the way for the development of next-generation energy storage technologies. In recent years, there has been a significant advancement in the development of MXene/graphene heterostructures as high-performance electrodes for Li-ion batteries, owing to their remarkable electrochemical properties. To gain a deeper understanding of the mechanisms underlying their promising experimental results, a systematic investigation was conducted using first-principles calculations, focusing on Ti_2CX_2(X = F, O, and OH) as representative MXenes. These calculations revealed several key insights into the behavior of MXene/graphene heterostructures. Firstly, the integration of graphene into MXene effectively mitigates the restacking effects of MXene layers, which is crucial for enhancing the overall performance of the electrode material. This prevention of restacking ensures that more electroactive sites remain accessible, facilitating rapid ion transport and contributing to the swift charging and discharging processes characteristic of high-performance Li-ion batteries. Additionally, the integration of graphene significantly enhances the electrical conductivity of the heterostructure, thereby improving the overall efficiency of charge transfer within the electrode material. Moreover, the presence of graphene strengthens the Li adsorption strength at the interface, while still maintaining high Li mobility, which is essential for achieving high specific capacities and long-term stability in Li-ion batteries. Furthermore, the mechanical stiffness of the heterostructure is substantially enhanced, ensuring structural stability during lithiation and contributing to the overall durability of the electrode material.

Among the studied materials, the Ti_2CO_2/graphene heterostructure emerged as the most promising candidate, exhibiting superior electrochemical performance compared to other MXene/graphene heterostructures. These findings provide valuable insights into the rational design of MXene-based electrodes for Li-ion batteries, paving the way for the development of next-generation energy storage technologies.The synthesis of MXene/graphene heterostructures typically involves several steps aimed at achieving a well-defined and high-performance electrode material. Firstly, MXene nanosheets are synthesized through the selective etching of MAX phases, followed by exfoliation to obtain individual MXene layers. Meanwhile, graphene is prepared through the reduction of graphene oxide (GO) using a suitable reducing agent, such as hydrazine. Once both MXene and graphene materials are prepared, they are combined using a dispersion-based method. Typically, the MXene dispersion is mixed with a graphene dispersion, and the resulting mixture is subjected to mechanical stirring and ultrasonic treatment to achieve a homogeneous colloidal solution. This colloidal solution is then deposited onto a substrate or template, followed by drying and thermal treatment to remove any residual solvents and promote the adhesion of MXene and graphene nanosheets. The resulting MXene/graphene heterostructure can then be further characterized and evaluated for its electrochemical properties, including Li-ion storage capacity, rate capability, and cycling stability. Overall, the synthesis of MXene/graphene heterostructures involves a series of carefully controlled steps aimed at optimizing the structural and electrochemical properties of the electrode material for high-performance Li-ion battery applications[43].

3D Synergistical MXene/Reduced Graphene Oxide Aerogel for a Piezoresistive Sensor

The development of a piezoresistive sensor utilizing an ultralight and super elastic aerogel, composed of MXene/reduced graphene oxide (MX/rGO) hybrid 3D structures, is detailed. This innovative sensor capitalizes on the synergistic properties of rGO and MXene, combining rGO's expansive specific surface area with MXene's high conductivity, while also leveraging the aerogel's rich porous structure. This combination results in superior performance compared to individual rGO or MXene components, particularly in terms of pressure sensitivity. The large nanosheets of rGO play a crucial role in preventing MXene's poor oxidation by effectively encapsulating MXene within the aerogel matrix. The piezoresistive sensor based on MX/rGO aerogel exhibits exceptional sensitivity (22.56 kPa-1), rapid response time (< 200 ms), and robust stability over 10,000 cycles. Importantly, this sensor can detect signals as low as 10 Pa, enabling precise pulse monitoring in adults. Its outstanding performance suggests potential applications in pressure distribution measurement, subtle strain detection, and monitoring various health activities. Overall, the MX/rGO hybrid 3D aerogel-based piezoresistive sensor showcases promising prospects for diverse real-world applications due to its remarkable performance characteristics. A hybrid MXene/reduced graphene oxide (MX/rGO) aerogel was successfully fabricated using a simple ice-template freezing technique and employed in a piezoresistive sensor. Leveraging the synergistic effect between MXene and rGO, this 3D aerogel exhibited remarkable performance in sensing applications, showcasing high sensitivity (22.56 kPa^{-1}), the rapid response time (< 200 ms), and excellent stability over 10,000 cycles. The sensor's limit of detection (LOD) of 10 Pa makes it highly practical for various applications.

Furthermore, compared to pure rGO aerogels, the mechanical properties and sensitivity of the MX/rGO aerogel were significantly enhanced. This sensor not only detects a wide range of pressures but also captures subtle physiological activities, such as wrist pulse beats. The fabrication method presented offers a cost-effective and scalable approach to developing sensors based on MXene hybrid materials, promising excellent performance for diverse applications[44].

Ti3C2Tx MXene/Graphene Nanocomposites: Synthesis and Application in Electrochemical Energy Storage

The synthesis and application of Ti_3C_2Tx MXene/Graphene nanocomposites in electrochemical energy storage represent a significant advancement in materials science. These nanocomposites combine the unique properties of MXenes and graphene to enhance energy storage device performance. In the synthesis process, Ti_3C_2Tx MXene flakes are exfoliated to single or few-layered nanosheets, typically through etching of layered MAX phases with hydrofluoric acid or other chemical etchants. Graphene sheets are then incorporated into the MXene nanosheets through various techniques such as mechanical mixing, chemical vapor deposition, or solution processing. The incorporation of graphene effectively prevents the restacking of MXene layers, increasing the active surface area available for charge storage, and enhancing the electrical conductivity of the composite material. This results in a high specific capacitance of the nanocomposites, which can reach up to 350 F/g in supercapacitors, indicating their high charge storage capacity. Furthermore, these nanocomposites exhibit excellent cycling stability, with negligible capacitance decay observed even after thousands of charge-discharge cycles. In lithium-ion battery applications, the nanocomposites demonstrate remarkable specific capacity values, exceeding 300 mAh/g, and exceptional rate capability, with capacity retention exceeding 80% at high charge-discharge rates. These impressive electrochemical properties stem from the synergistic effects between MXene and graphene, where MXene provides pseudocapacitive charge storage while graphene enhances electronic conductivity. The MXene/Graphene nanocomposites hold promise for addressing the increasing demand for high-performance energy storage devices in various fields, including portable electronics, electric vehicles, and grid storage systems, contributing to the advancement of sustainable energy technologies[32].

CONCLUSION

The production and characterization of MXene/graphene hybrid composites is a critical first step toward the development of novel materials with a broad variety of applications. From gas detection to water purification, energy storage, and electromagnetic interference shielding, these hybrids hold great promise thanks to their customizable fabrication processes and comprehensive characterization methods, which are described in this study. Prospective studies should focus on enhancing synthesis techniques and characterization strategies even more. By incorporating MXene/graphene hybrids into cutting-edge technology like flexible electronics, biomedical gadgets, and environmental remediation systems, many industries could experience drastic change, and pressing global concerns could be tackled. Interdisciplinary collaboration is necessary to fully use MXene/graphene hybrids and pave the way for efficient and sustainable materials science and technology.

In conclusion, the synthesis and characterization of MXene/graphene hybrid materials have marked a significant advancement toward the development of advanced materials with a broad variety of applications. The study that is being presented shows how exceptional these hybrids may be in a variety of applications, including gas sensing, water purification, energy storage, and electromagnetic interference shielding. Scientists have produced materials with amazing properties, such as enhanced sensitivity, selective removal of impurities, high conductivity, and higher energy storage capacity, by leveraging the synergistic effects of MXene and graphene. Customized techniques of adjustment are provided by the mentioned fabrication processes, which include the filtering process for composite membranes, the careful mixing for multifunctional sensor components, and the electrostatic self-assembly for electrode films. comprehensive techniques for characterization have provided valuable insights into the morphological, chemical, and structural properties of these hybrid materials, which are essential for understanding their behavior and realizing their full potential. Furthermore, the production of GO/MXene composite membranes for filtration applications offers a scalable and controllable means to customize membrane properties by altering the GO to MXene mass ratios. Characterization techniques like AFM, XRD, SEM, XPS, FT-IR, surface contact angle measurement, UV-visible absorption spectroscopy, and SEC provide essential information on the structure, morphology, and chemical composition of membranes to increase filtration efficiency and selectivity. Looking at the future aspects the versatility of MXene/graphene composites a broad range of applications in various fields of life supporting various possibilities for future research development. More exploration in this field will likely lead to the discovery of novel hybrid materials with advanced enhanced properties and functionalities. Furthermore, the integration of MXene/graphene composites into emerging technologies, such as flexible electronics, biomedical devices, and environmental remediation systems, can revolutionize various industrial aspects addressing different global challenges in the field of biomedical sciences. As a result of collaboration and innovation flourish, MXene/graphene composites are poised to play a pivotal role in shaping the future of materials science and technology, offering sustainable and efficient solutions to meet the upcoming needs of society.

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