

**Advances in  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated Conductive Textiles for Wearable Biomedical Sensors in Health Monitoring**

*George Kwame Fobiri\*, Ebenezer Kofi Howard, Timothy Crentsil, Charles Frimpong, Theo Hughes-Riley*

G.K. Fobiri, T. Crentsil

Department of Fashion Design and Textiles Studies, Kumasi Technical University, AK040 K, Ghana

E-mail: kfobiri@gmail.com / george.kfobiri@kstu.edu.gh

E. K. Howard, C. Frimpong

Department of Industrial Art, Kwame Nkrumah University of Science and Technology, AOK447, Ghana.

T. Hughes-Riley

Nottingham School of Art and Design, Nottingham Trent University, UK

Keywords: conductive textiles,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes, biomedical sensors, e-textiles, smart textiles, MXenes-integrated textiles, health monitoring

The discovery of MXenes has yielded several innovative approaches to manufacturing conductive materials for improved performance in several sectors. Among the various types of MXenes, Titanium carbide MXene ( $\text{Ti}_3\text{C}_2\text{T}_x$ ) is widely applied in advanced material design due to its desirable characteristics. Integrating  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes with textiles promises to create a new generation of textile materials with enhanced properties for application in various devices, including wearable biomedical sensors. It has been observed that the application of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes with textiles as a base material in the health sector has not received significant attention, hence, there is a need for a critical review to allow for greater insights into the prospects of using this 2D material in the textile industry toward smart healthcare delivery. This review has been conducted to fill this gap by delving into the application of MXenes in textile manufacturing toward biomedical sensor design. Findings show that  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes are promising materials in advancing wearable textile electronics, especially for biomedical sensor design. Future studies to explore the integration of MXenes-based biosensors into the IoT, and methodologies that are harmless to the environment and

human health, are recommended to ensure seamless healthcare delivery with sensors and sustainable smart textile manufacturing.

- $\text{Ti}_3\text{C}_2\text{T}_x$  MXene is widely applied in advanced material design due to its desirable characteristics.
- Areas including energy storage/conservation, environmental applications, electronics and optoelectronics, aerospace and defense, agriculture, construction and infrastructure, transportation and automotive have explored the excellent properties of MXenes.
- Integrating  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes with textiles is an adventurous approach to increasing the capabilities of the textiles for wearable electronics for health monitoring.
- Innovative sensors and smart textiles have been manufactured with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes for healthcare applications

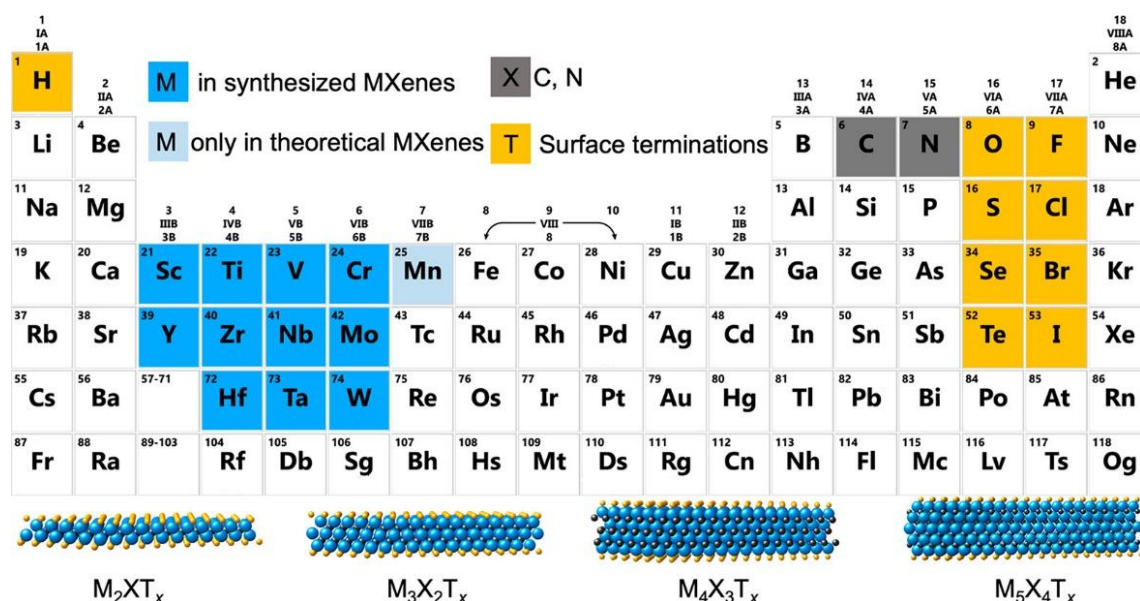
## 1. Introduction

Electronic textiles (e-textiles) form a significant part of the larger wearable electronics group that has recently gained popularity in biomedical applications for enhanced healthcare delivery.<sup>[1-3]</sup> Electronics textiles can be produced using various methods, including the attachment of electronics onto or into existing textiles, the incorporation of conductive materials during the textile manufacturing stage, or the incorporation of advanced electronics into fibers or yarns.<sup>[4]</sup> One method of imbuing electronic functionality to textiles or yarns is through treatments and coatings. Textiles are treated in several ways, including integrating conductive materials to enrich and diversify their performance in wearable technology. Ordinary textiles (fibers, yarns, or fabrics) are reinforced with advanced materials to render them more conductive. Examples of advanced conductive materials include graphene, MXenes, molybdenum disulfide ( $\text{MoS}_2$ ), and polymers such as polyaniline, polypyrrole, poly(3,4-ethylenedioxythiophene), and polythiophene.<sup>[5-8]</sup> These materials have recently been employed in smart textile production due to their good conductive properties.

After discovering graphene, a significant conductive two-dimensional (2D) material in 2004,<sup>[9-11]</sup> several studies have researched functional conductive materials, resulting in the discovery of MXenes in 2011.<sup>[12-14]</sup> MXenes are typically 2D materials with the formula  $\text{M}_{n+1}\text{X}_n\text{T}_x$ , where  $M$  is an early transition metal,  $X$  is nitrogen or carbon,  $n$  ranges between 1 and 3, and  $T$  represents the functional groups including -O, -F, or -OH.<sup>[15]</sup> The composition of the element(s), represented by  $X$  in a given MXene, determines the characteristics and uses of

such MXenes. **Figure 1** shows a periodic table indicating elements that are used for MXene synthesis. In MXene production, the A-layers are etched from MAX phases to reveal transition metal carbides, nitride, or carbonitrides with a characteristic layered structure.<sup>[16]</sup> MXenes are good reinforcement materials with adjustable surface functional groups, making their surface design more feasible.<sup>[17]</sup> For instance, the Titanium carbide MXene ( $\text{Ti}_3\text{C}_2\text{T}_x$ ) type has been identified as a potential support site for adhering metal oxide semiconductors in low-temperature gas sensing materials manufacturing.<sup>[18]</sup> Recent advancements have been observed in various sectors regarding the application of MXene-reinforced materials. Areas including energy storage and conservation,<sup>[19-24]</sup> environmental application,<sup>[25-27]</sup> electronics and optoelectronics,<sup>[28-30]</sup> aerospace and defense,<sup>[31, 32]</sup> agriculture,<sup>[33, 34]</sup> construction and infrastructure, transportation and automotive, etc. have explored the excellent properties of MXenes.

$\text{Ti}_3\text{C}_2\text{T}_x$  MXenes are among the most popular 2D materials receiving the attention of scholars. This is due to their wide usage in energy storage, their good hydrophilicity, excellent mechanical strength, and good electrical conductivity, in addition to them being able to provide a large surface area:<sup>[35, 36]</sup> This makes them good potential resources for electrodes in supercapacitors.<sup>[37]</sup>  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes also possess desirable optical properties for many applications, with these properties including light-induced heating, good transparency, excellent plasmonic effect, and a wavelength ranging between 300-500 nm, which renders them more capable of absorbing ultraviolet-visible light.<sup>[38, 39]</sup> As 2D materials that were scientifically synthesized in 2011,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes originated from  $\text{Ti}_3\text{AlC}_2$  MAX through the etching of Al layers with hydrofluoric acid.<sup>[40, 41]</sup>  $\text{Ti}_3\text{C}_2\text{T}_x$  happened to be the first MXenes group invented among other numerous types discovered such as Niobium-based ( $\text{Nb}_2\text{CT}_x$ ), Molybdenum-based ( $\text{Mo}_2\text{CT}_x$ ), Vanadium-based ( $\text{V}_2\text{CT}_x$ ), and  $\text{Ti}_2\text{CT}_x$  MXenes. The qualities of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes make them applicable in wearable devices for healthcare applications, and therefore,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes are the focus of this review. Over the past few years, the potential for electronic textiles in the health sector has caught the attention of researchers who are delving into the materials involved in their production and their mode of application. Examples include recent studies that present Carbon Nanotubes (CNTs), graphene-based, Transition Metal Dichalcogenides (TMDs), and MXene-based conductive materials that are reported to be suitable for integrating into wearable devices meant for healthcare applications.<sup>[42-47]</sup>

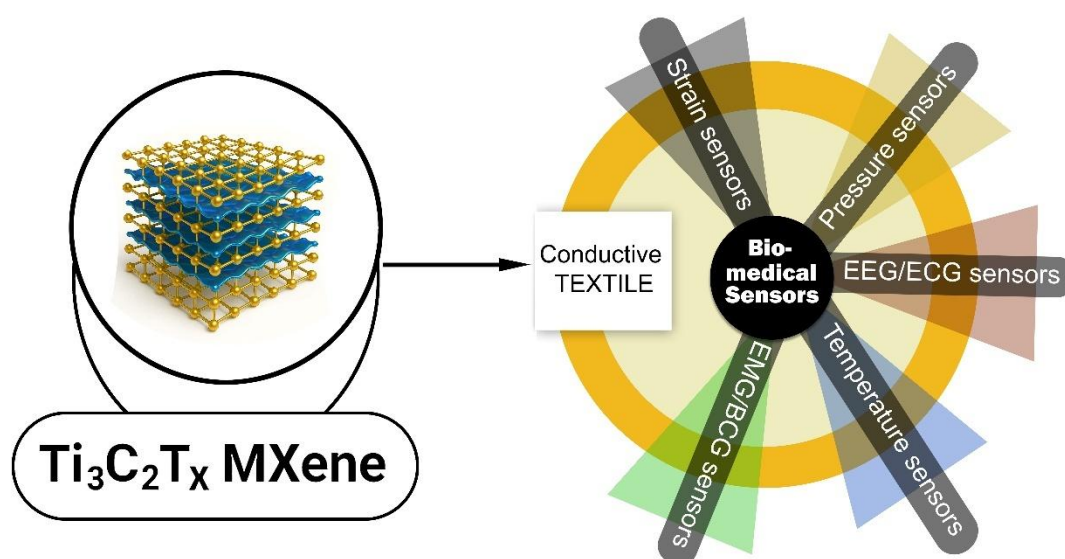


**Figure 1:** Periodic table showing elements that are used for mxene synthesis. All colored elements are suitable for manufacturing mxenes, with four structures of mxenes presented beneath the table. Reprinted from Gogotsi and Huang<sup>[48]</sup> with permission: © 2021 American Chemical Society.

Integrating  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes with textiles is an adventurous approach to increasing the capabilities of the textiles for wearable electronics for health monitoring. It is observed that textiles are the best supporting media for the production of devices that are used in personal thermal tracking, and a recent study into this area has shown a device for this application that relied greatly on MXene nanosheets.<sup>[44]</sup> In healthcare delivery,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated textiles find applications in sensor manufacturing for monitoring human physiological vitals such as temperature, pressure, strain, heart pulse, glucose, and lactate through the utilization of their conductive features. In advanced textile production for biomedical purposes, sensors play a key role as they have become more versatile and sophisticated due to the materials employed recently in the manufacturing of advanced technological equipment.<sup>[49]</sup> In the same vein, conductive materials are key in smart textile designing for sensing various parameters requiring electron flow for responsive actions. They are therefore desired mostly in smart textiles for electrical connections between components or devices.<sup>[50]</sup> This gives prospects for using MXene-integrated textiles in the medical sector.

Despite the many desirable features of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes, their integration with textiles for applications in the health sector has not received much attention. Therefore, rigorous discussion is needed for an in-depth understanding of the progress made with this 2D material (specifically  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene), especially in the health sector, where sensors play a key role in

most devices employed for practice. Subsequently, this review has been conducted to provide knowledge on the improvements made in the health sector through the use of MXenes integrated with textiles. It deliberates on recent advancements in conductive materials, especially  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based textiles, and their prospects in wearable sensors for monitoring health parameters. The review also discusses the synthesis of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes, sensors integrated with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene, and  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based textile materials in wearable electronics, and a discussion on research directions. **Figure 2** shows various biomedical sensors produced with textiles enhanced with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene.



**Figure 2:** Illustration of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated conductive textiles for Biomedical Sensors.

## 2. Biomedical Sensors in Healthcare Delivery

In the era of technological advancements, where the Internet of Things (IoT) is the topic of the day, biomedical sensors are crucial for remote patient monitoring.<sup>[51]</sup> Also, enzymatic detection technology has increased the application of sensors in the health sector.<sup>[52]</sup> In the quest to obtain reliable and robust sensors, scholars have conducted extensive research with diverse materials and technologies. Textile sensors, for instance, have been researched intensively due to their lightweight, comfort, flexibility, ability to resist deformation, and easy integration into smart clothing.<sup>[2, 53-55]</sup> Research shows that smart textile manufacturing is an innovative and feasible approach to promoting remote healthcare, especially for monitoring heart rate (a significant health parameter), and other factors such as strain and pressure.<sup>[56]</sup> A pressure sensor empowered by a highly sensitive capacitive ionotronic in wearable textile electronic systems toward biomedical applications is shown in **Figure 3a**.<sup>[53]</sup> It is reported

that a highly sensitive pressure sensor of up to  $308 \text{ nF kPa}^{-1}$  was obtained with the help of high- $k$  ion-gel film. A textile-based wireless pressure sensor developed for remote tactile sensing has been reported in a previous study to demonstrate the capabilities of textile-based sensors in healthcare applications.<sup>[57]</sup>

Moreover, various designs of biomedical sensors, especially textile-based, have been reported with evidence of their feasibility in healthcare delivery and the specific health parameters they are designed to measure. For instance, a wound bandage with an incorporated fibrous optical sensor for wound healing and peroxide monitoring is shown in **Figure 3b**.<sup>[58]</sup> Again, a recent study presents a sensor based on surface-enhanced Raman scattering technology for sweat glucose detection and lactate analysis,<sup>[59]</sup> shown in **Figure 3c**. Liu et al.<sup>[60]</sup> also report on a textile-based pressure sensor for integrating into a garment for smart health monitoring: The sensor's design is such that the top is an elastic piezoresistive sensing fabric. At the same time, the bottom comes with durable textile-based interdigital electrodes, presented in **Figure 3d**. The pressure sensor is said to possess desirable and functional characteristics such as a high sensitivity of  $3.42 \text{ kPa}^{-1}$ , a fast response and recovery time of 32 ms/4 ms, good stability after 10,000 loading and unloading cycles, and excellent mechanical strength, functioning after 10,000 bending cycles. Another textile-based respiratory sensor has been designed and validated for medical monitoring in neonatal intensive care units.<sup>[61]</sup> A recent study also presented biomedical sensors capable of detecting reproductive hormones to demonstrate how gold metasurfaces and graphene could be employed in highly sensitive sensor manufacturing.<sup>[62]</sup>

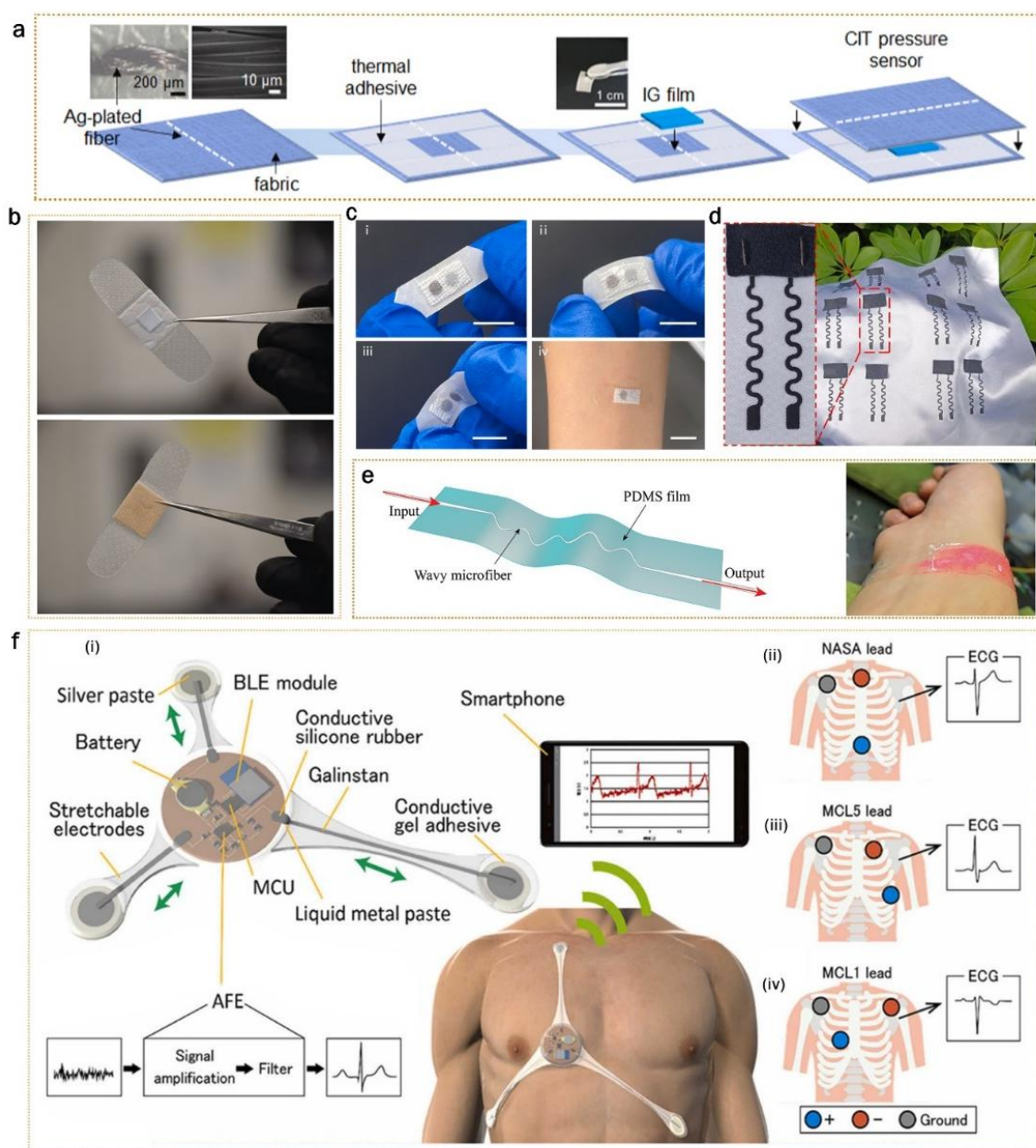
The fact that novel technologies are required for real-time sensing to monitor human health in advanced healthcare has increased the design and application of biomedical sensors and related devices.<sup>[63]</sup> In addition to the previously stated concepts regarding biomedical sensors, evidence of their design and application in smart healthcare is seen in several other studies such as antenna-based plasmonic biomedical sensor,<sup>[64]</sup> a biomedical sensor designed for tuberculosis detection, with an improved quality factor of 10731, a detection limit of  $5.87 \times 10^{-6}$ , and excellent sensitivity of  $1738.7 \text{ nm/RIU}$ ,<sup>[65]</sup> a photonic-based biomedical sensor for detecting brain tumors,<sup>[66]</sup> and a stretchable wearable sensor designed with optical microfiber presented in **Figure 3e**,<sup>[67]</sup> which has been used to monitor the pulse wave. Moreover, **Figure 3f** shows a highly transformable electrocardiograph for sensing heart diseases, measuring electrocardiogram (ECG) signals.<sup>[68]</sup> It is worth noting that health monitoring with biomedical sensors encompasses detecting numerous physiological parameters, which collectively prove the indispensability of biosensors in healthcare applications. Vital signs monitoring sensors

for detecting heart electrical activity (ECG sensors), heart rate or blood oxygen saturation (Photoplethysmography -PPG sensors), blood oxygen levels (oximetry sensors), and breathing rhythm (respiration sensors) play a key role in wearable electronics in health monitoring. Moreover, one could mention other biomedical sensor types for exclusive applications like biochemical and metabolic monitoring (pH, hormone, sweat analysis, and hydration sensors), neuromuscular/neural activity monitoring (Electroencephalography-EEG, Electromyography-EMG, Ballistocardiography-BCG), motion and activity sensing (accelerometers, pressure sensors). These sensors cannot be overlooked in the quest to adopt smart healthcare in the medical field.

Developed in the 1930s, PPG sensors have advanced in design and application, later changing to pulse oximeters, leading to their usage in heart rate monitoring in newly born babies, for obtaining heart rate and oxygen saturation from patients, and detecting respiratory diseases, making them significant sensors during the COVID-19 era.<sup>[69-74]</sup> Through pulse oximetry, oxygen saturation of haemoglobin in arterial blood is invasively and continuously monitored for smart healthcare.<sup>[75]</sup> From research, concerns have been raised about the accuracy of pulse oximetry from a racial perspective, arguing that patients with dark skin do not fully benefit from pulse oximetry technology.<sup>[76-78]</sup> Notwithstanding, studies have shown the significant role of PPG sensors in the biomedical field, where they help detect oxygen saturation in patients using diverse approaches. For instance, Han et al.<sup>[79]</sup> improved PPG and oxygen saturation (SpO<sub>2</sub>) sensing by employing ambient light oximeters. Apart from improving biomedical sensing, this technology also helps reduce the size of PPG and SpO<sub>2</sub> sensors, as light-emitting diodes (LEDs), which require additional attachments for effective performance, are avoided. Also, Zavaleta et al.<sup>[80]</sup> introduced the Pressure Pro, a health monitoring prototype with blood pressure and SpO<sub>2</sub> sensors coupled with wireless connectivity that can be used in rural areas for effective healthcare. With these approaches, PPG sensors perform incredibly in the biomedical field for smart healthcare.

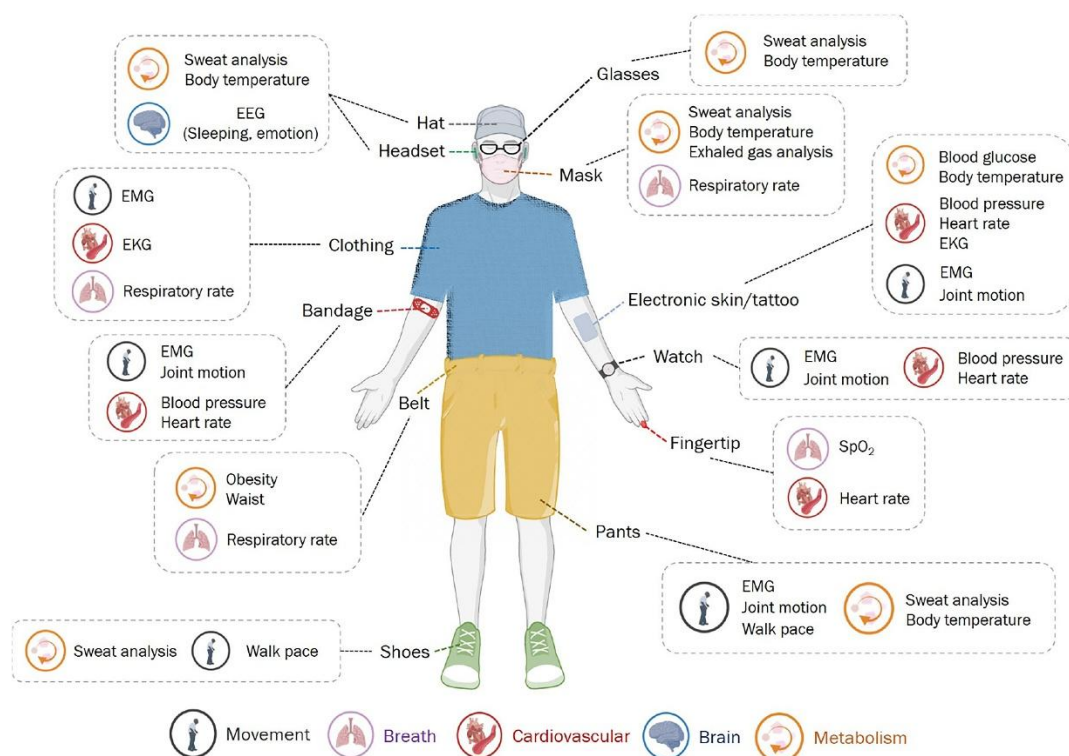
In addition, biomedical activities such as hormone, pH, and sweat analysis are also performed easily with electrochemical sensors in healthcare delivery.<sup>[81, 82]</sup> In wound healing, electrochemical sensors are embedded in wearable devices to effectively monitor pH, predict infections, and assess healing status in chronic wound treatment among patients.<sup>[83]</sup> Also, detecting sweat metabolites with electrochemical sensors has led to improved healthcare by providing patients' health information via biomarkers in the sweat for medical practitioners to act proactively.<sup>[84]</sup> Following this, Hua et al.<sup>[85]</sup> manufactured an electrochemical sensor for monitoring ammonium ions (NH<sub>4</sub><sup>+</sup>) in sweat with a composite of metal-organic frameworks

(MOFs) and reduced graphene oxide (rGO). Results indicate improved performance with a Nernstian response of  $59.2 \pm 1.5$  mV/log  $[\text{NH}_4^+]$ , detection limit of  $10^{-6.37}$  M, and a linearity range of  $10^{-6}$  to  $10^{-1}$  M. Moreover, biosensors for detecting neuromuscular/neural activities, such as EMG, EEG, etc., have advanced healthcare delivery. For instance, Nyni et al. [86] developed a wireless monitoring system for detecting ECG, EEG, and EMG with integrated biosensors that can sense changes in patients' hearts, detect neuronal activity of the brain, and monitor body muscles. From the various sensor inventions observed in previous studies, it could be said that the health sector has been one major area targeted by researchers in advanced sensor development for smart applications. **Figure 4** shows a scheme of detectable bio-signals on the human body and their wearable detections. It is classified according to anatomical locations and associated physiological systems. It highlights activity signals, including ECG, EMG, and EEG.



**Figure 3:** Various designs of biomedical sensors for smart healthcare delivery for the literature. (a) The manufacturing process for a textile-based capacitive ionotronic pressure sensor. Reprinted from Keum et al. <sup>[53]</sup> with permission: © 2021 Elsevier. (b) A wound bandage integrated with optical fiber samples (textile-based sensor) for reactive oxygen species detection. Reprinted from Safaei et al. <sup>[58]</sup> with permission: © 2021 Wiley-VCH. (c) Photographs of a textile-based biomedical sensor for sweat glucose detection and lactate analysis. The appearance and flexibility of the sensor at (i) normal, (ii) bent, (iii) folded states. The scale bar represents 10mm. Reprinted from Yu et al. <sup>[59]</sup> with permission: © 2024 Elsevier. (d) Photograph of a textile-based pressure sensor for integration into a garment for smart health monitoring. Reprinted from Liu et al. <sup>[60]</sup> with permission: © 2023 Elsevier. (e) Schematic illustration and photograph of a stretchable optical sensor stuck on a wrist.

Reprinted from Zhu et al. <sup>[67]</sup> with permission: © 2021 Wiley-VCH. (f) Schematic illustration of a transformable electrocardiogram device. (i) Summary of the device structure. (ii-iv) Electrode position with respective electrocardiograms. Reprinted from Takaya et al. <sup>[68]</sup> with permission: © 2021 American Chemical Society.



**Figure 4:** Schematic illustration of detectable bio-signals on the human body and their wearable detections. Reprinted from Lu et al. <sup>[87]</sup>

## 2.1. Biocompatibility Considerations for Biomedical Sensors

With an increased integration of biosensors in smart healthcare devices, biocompatibility has become a requisite feature to improve patient comfort, safety, device accuracy, and sustainable performance for easy adoption in healthcare. Biocompatibility is a feature that allows biomedical devices to perform effectively without causing harm to the body. The human body can react to external materials, like biosensors, to cause undesirable side effects such as skin irritation, discomfort, and allergic reactions. The body must be free and receptive to biomedical devices, which are mostly implanted or attached to the skin. Sensors and implantable devices that lack biocompatibility features require surgeries and critical interventions to be removed from the body, resulting in the risk of infection and the escalation

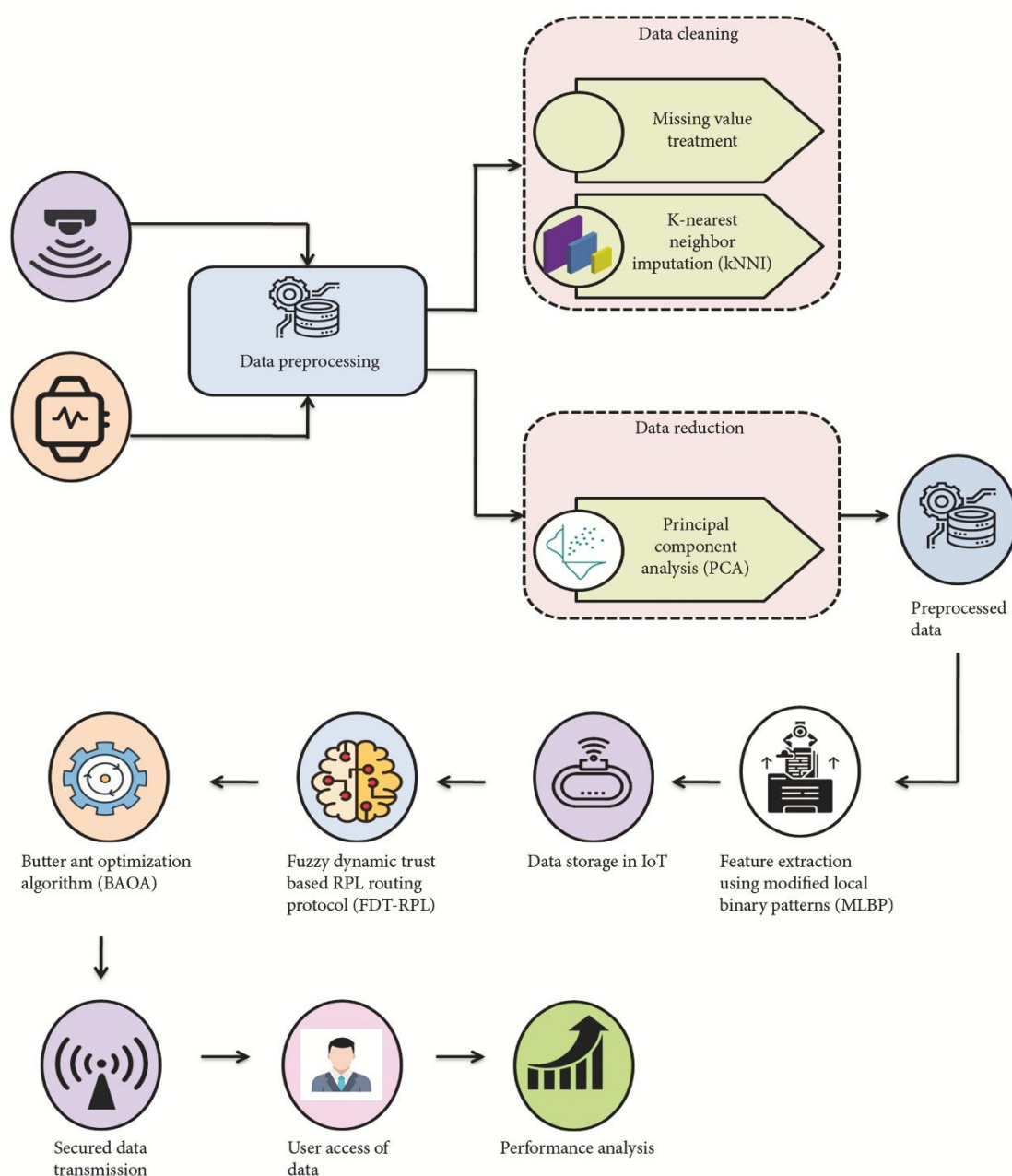
of health complications.<sup>[88]</sup> Hence, there is a need for biocompatible and biodegradable devices. The ability of various biomedical sensors to conform mechanically to the human skin and tissue is a significant determinant of biocompatibility and accurate sensing abilities.<sup>[89]</sup> Recent research shows how innovative materials could be adopted in sensor design to ensure biocompatibility in sensors for healthcare. It is observed that stretchable/conductive hydrogels and ionogels with ionic liquids are candidates for pressure and strain sensor manufacturing, although they have shortcomings of instability (hydrogel), toxicity, and non-biocompatibility (ionogel).<sup>[90]</sup> Combating these challenges, Wang et al.<sup>[90]</sup> created eutectogels consisting of deep eutectic solvents, waterborne polyurethane, and Tannic acid with desirable properties such as self-adhesive, stretchable, nonvolatile, and biocompatible to manufacture biopotential electrodes, pressure, and strain sensors. The eutectogels have elongation at break of 178%, ionic conductivity of 0.22 mS/cm, and adhesion force of 12.5 N/m to skin. These remarkable properties make them suitable for designing biocompatible wearable devices for healthcare delivery.

Also, biocompatible hydrogels are crucial in sensor design to ensure safety when adopting wearable devices for healthcare applications. Apart from providing safety for skin contact when adopted for sensor design, they ensure performance in biosensors for healthcare purposes. In considering biocompatibility, He et al.<sup>[91]</sup> manufactured a biocompatible pressure/strain sensor with a conductive hydrogel consisting of silk fibroin, polyacrylamide, graphene oxide, and poly(3,4-ethylenedioxythiophene): poly(styrenesulfonate). The resulting biocompatible sensors exhibited a wide sensing range (strain, 2%–600%; pressure, 0.5–119.4 kPa) and good stability. This indicates a promising future for biosensors. It could be said that, as biomedical sensors are required to possess biocompatibility properties, conductive hydrogels are a good resource to consider in sensor manufacturing for safe and continuous monitoring of health parameters in smart healthcare.

## 2.2. Data Transmission in Smart Healthcare

Data obtained from patients is crucial for understanding their health condition upon analysis, especially with advanced technologies such as Artificial Intelligence (AI), IoT systems, and Machine Learning.<sup>[92]</sup> In biomedicine, wearable devices transmit a huge amount of data to IoT devices using sensors.<sup>[93]</sup> Unfortunately, data on the IoT is exposed to threats and attacks.<sup>[94-97]</sup> Hence, data gathered with smart wearable devices requires ethical handling and transmission for subsequent analysis and intervention in healthcare delivery. Also, aiming at going smart in healthcare recently, wireless data transmissions have been adopted, requiring

strict encryption for effective and continuous management of data ethically, confidentially, and professionally. It is observed that transmitting data wirelessly is considered safer than the traditional wired approach. Wireless transmission ensures flexible data handling, convenience, and secure protocols, especially when encryption is considered. With data security as a priority in the IoT era, measures have been proposed to ensure safe wireless data transfer. In this vein, Refaee et al.<sup>[93]</sup> presents a secure and scalable framework for healthcare data transmission under the IoT system. This was developed by incorporating various techniques, including data processing, feature extraction, and secure routing protocols. The framework allows data collection from IoT sensors and wearable devices, processing the collected raw data through data cleaning and reduction, then extracting features using fuzzy dynamic trust-based RPL routing combined with the Butter Ant Optimization algorithm. A secure routing protocol (FDT-RPL) ensures data encryption and transmission security for improved healthcare delivery using wearable devices and IoT systems. The methodology, as part of the wireless approach to data transfer from sensors and devices, helps protect sensitive data that needs to be kept confidential by healthcare providers. **Figure 5** shows the proposed framework for the safe transfer of data from wearable biomedical devices to healthcare providers.



**Figure 5:** Schematic illustration of a proposed framework for the safe transfer of data from wearable biomedical devices to healthcare providers. Reprinted from Refaee et al. <sup>[93]</sup>

### 3. Synthesis and characterization of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene

The preparation of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene is generally done through two methods including; the top-down and bottom-up approaches.<sup>[98-101]</sup> As largely applied methods in chemistry to produce materials, the top-down approach involves the removal of a phase from a compound material with special chemicals, while the bottom-up approach involves the production of a material with different elements as a building block.<sup>[102]</sup> Again, contrary to the bottom-up approach, a larger number of precursor materials are required in the top-down synthesis of MXenes, and

fewer organic/inorganic molecules/atoms are needed to manufacture the MXene structures.<sup>[100]</sup> These broad approaches come with various laboratory techniques uniquely employed to obtain a thin sheet or 2D material (such as  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene) with highly conductive properties for wearable devices. For instance, it is established that the conductivity and stability of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene could strategically be improved during its synthesis out of  $\text{Ti}_3\text{AlC}_2$  MAX phases by adding more moles of titanium and aluminum during sintering.<sup>[103]</sup> The top-down approach offers several advantages such as enabling total control over the process to determine the structure and composition of the MXene under synthesis, better potential for industrial scale-production, since the method can be adopted for mass-production, and is cost-effectiveness as complex procedures are minimized: This makes the top-down the preferred approach over the bottom-up approach.<sup>[101]</sup> The bottom-up approach, however comes with its advantages such as the ability to yield high-quality thin 2D films.<sup>[98]</sup> having control over the morphology of the resulting MXene, easy functionalization, and proper and efficient utilization of atoms.<sup>[104]</sup>

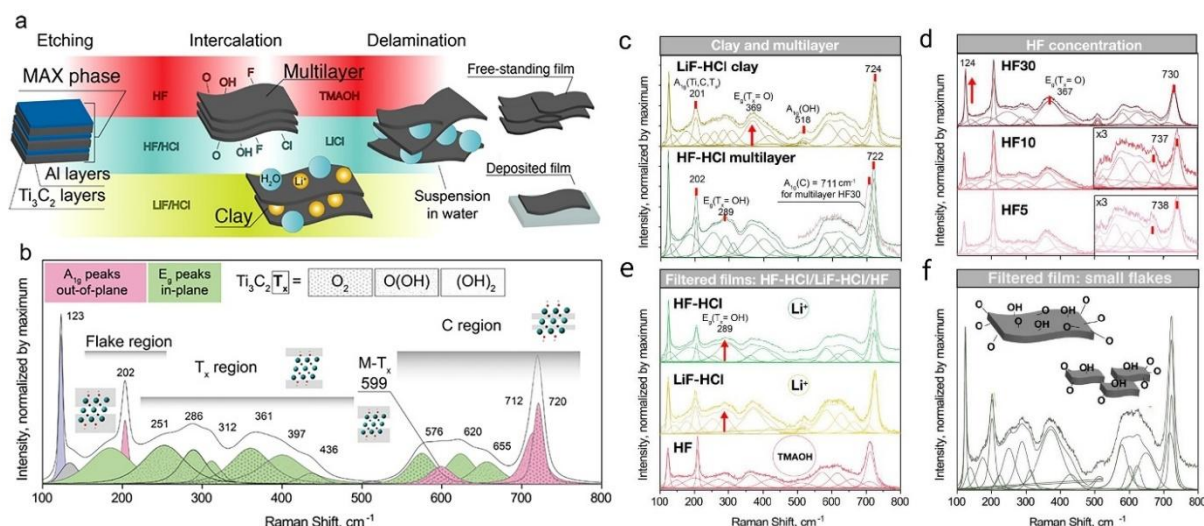
As part of the synthesis of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes, scholars have underlined step-by-step guidelines for the processing and acquisition of quality MXenes for a variety of applications, making good use of either the top-down approach or bottom-up approach, and sometimes both approaches. Thakur et al.<sup>[105]</sup> give an account of the synthesis of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene using both hydrofluoric (HF) and hydrochloric (HCl) acids for the etching of the MAX phase, and delamination with lithium chloride (LiCl). Similarly, Liu et al.<sup>[106]</sup> studied the exfoliation of MXene nanosheets in a study and discovered a one-step method known as ECO-ME, which is reported to be more efficient compared to conventional exfoliation methods. Again, Pattanayak et al.<sup>[107]</sup> present the diazonium salt-based approach to the synthesis of MXenes by exploring agents such as 4-carboxy benzene diazonium tetrafluoroborate and 4-carboxy benzene diazonium ion for delamination and exfoliation respectively. The study also reports on the situation where the 4-carboxy benzene diazonium ion also serves the purpose of intercalation coupled with the exfoliation abilities of the chemical agent simultaneously. Pazniak et al.<sup>[108]</sup> also report a cost-effective approach to synthesizing  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene from a precursor ( $\text{Ti}_3\text{AlC}_2$ ), where grinding is combined with self-propagation high-temperature synthesis. The synthesis of Titanium-based MXenes with top-down and bottom-up approaches is therefore prevalent in the literature.  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene production is such that both approaches could be employed in its synthesis at different stages for varied applications.

### 3.1. Top-down Approach

The top-down approach of MXene synthesis involves the use of various methods such as using hydrofluoric acid for etching, hydrochloric acid or lithium fluoride etching, fluoride-based salts, mechanical milling, and halogen etching.<sup>[109]</sup> In this process, the A-layers, including Aluminum (Al), Gallium (Ga), Silicon (Si), and Sn (Tin) in the precursor (MAX phase), are removed.<sup>[110-112]</sup> In the top-down approach, the A-layers are easily removed from the MAX phase as a weaker bond exists between M-A and a stronger covalent or ionic bond exists between M-X.<sup>[113]</sup> It is worth noting that MXene synthesis with the top-down approach becomes problematic when there is a strong bond between M-A and a weaker bond between M-X, or a strong one between both M-A and M-X. Again, synthesis becomes difficult when a weak bond exists in both M-A and M-X.<sup>[114]</sup> Regarding the top-down method of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene synthesis, a common approach is Hydrofluoric acid (HF) etching involving the use of an aqueous solution of HF to etch off the Al from the bulk  $\text{Ti}_3\text{AlC}_2$  material to obtain MXene with an improved surface.<sup>[101]</sup> This type of etching has received several critiques due to the harmful nature of HF, as it is both highly corrosive and a poison that can be absorbed through direct skin contact. Subsequently, scholars such as Ghidui et al.<sup>[115]</sup> have investigated the use of lithium fluoride (LiF) and hydrochloric acid (HCl) solutions in the synthesis of MXenes, which significantly do away with intercalation to delaminate MXenes etched with HF, as the in situ formation of HF simplifies the process. According to Naguib et al.<sup>[13]</sup>, using LiF-HCl as an alternative solution boosted the production of MXenes in regions where HF is not allowed in laboratories due to its harmful nature.

The top-down approach with LiF-HCl has been explored by Sarycheva and Gogotsi<sup>[116]</sup> to synthesize  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene, which was subsequently analyzed with Raman spectroscopy, as presented in **Figure 6**. In their exploration, the authors report the initial mixing of LiF and HCl, followed by the etching of the MAX phase with varied concentrations (5%, 10%, 20%, and 30%) of the aqueous HF formed in situ, as shown in Figure 6a. The synthesized  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene was then analyzed with Raman spectroscopy, with the spectrum being segmented into flake,  $\text{T}_x$ , and carbon regions as seen in Figure 6b: The characteristics of the spectra are shown in Figure 6(c-f). Figure 6c indicates the clay and multilayer spectra treated with LiF-HCl and HF-HCl respectively which showed varied peaks and vibrational modes of  $201\text{ cm}^{-1}$  ( $\text{A}_{1g}$ ),  $369\text{ cm}^{-1}$  ( $\text{E}_g$ ),  $518\text{ cm}^{-1}$ , and  $724\text{ cm}^{-1}$  for the LiF-HCl clay, and  $202\text{ cm}^{-1}$ ,  $289\text{ cm}^{-1}$  ( $\text{E}_g$ ),  $711\text{ cm}^{-1}$ , and  $722\text{ cm}^{-1}$  for HF-HCl multilayer. Symmetric stretching and in-plane atomic movements coupled with bond stretching and higher frequency lattice interactions can be deduced from these outputs. Figure 6d also shows the HF concentration and peak

variations of HF5 (738  $\text{cm}^{-1}$ ), HF10 (737  $\text{cm}^{-1}$ ), and HF30 (367  $\text{cm}^{-1}$ , 730  $\text{cm}^{-1}$ ), indicating a slight shift in vibrational spectra as the HF concentration increased. In Figure 6e, various filtering (HF-HCl, LiF-HCl, and HF) were presented with only HF-HCl etching showing a peak shift of 289  $\text{cm}^{-1}$ . Finally, Figure 6f shows filtered films of  $\text{Ti}_3\text{C}_2\text{T}_x$  flakes obtained through HF-HCl etching.



**Figure 6:** Schematic illustration of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene synthesis and Raman spectroscopy analysis of the synthesized MXene from the literature. (a) Synthesis procedures of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene including etching, intercalation, and delamination. (b) Raman spectrum obtained from the synthesized  $\text{Ti}_3\text{C}_2\text{T}_x$  showcasing the flake,  $\text{T}_x$ , and carbon regions. (c) Raman spectra of clay and multilayer MXenes. (d) The effect of varied HF concentration on Raman spectra of the synthesized mxene ( $\text{Ti}_3\text{C}_2\text{T}_x$ ). (e) The impact of HF-HCl, LiF-HCl, and HF on delaminated filtered films. (f) Raman spectrum of filtered film of  $\text{Ti}_3\text{C}_2\text{T}_x$  flakes obtained through HF-HCl etching. Reprinted from Sarycheva and Gogotsi<sup>[116]</sup> with permission: © 2020 American Chemical Society.

### 3.2. Bottom-up Approach

The bottom-up approach to synthesizing MXenes often starts with organic or inorganic molecules/atoms built gradually to form layers of 2D materials.<sup>[117, 118]</sup> MXenes synthesized with the bottom-up approach are known for their crystalline quality, more controlled structure, and size.<sup>[119-121]</sup> These 2D materials are difficult to etch through the top-down synthesis method, hence, the bottom-down approach is an alternative. Regarding  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene synthesis with the bottom-up approach, Zhang et al.<sup>[122]</sup> prepared a composite material

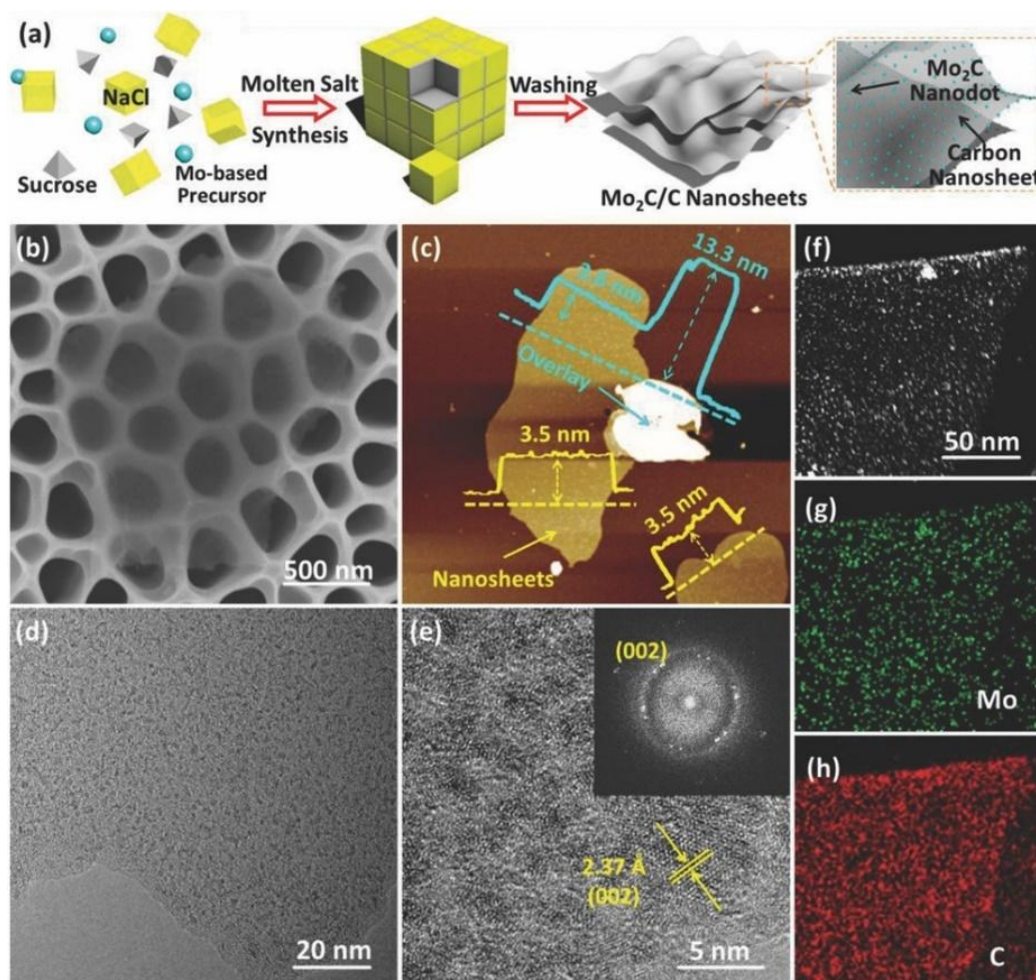
comprising of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene, cobalt, and 1,4-benzenedicarboxylate to form a MXene-metal-organic framework. In this experiment,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene was coupled with the metal-organic framework to obtain the  $\text{Ti}_3\text{C}_2\text{T}_x$  – CoBDC composite for an improved separator in lithium-sulfur batteries. Various techniques explored by scholars under the bottom-up approach include chemical vapor disposition (CVD), physical vapor deposition (PVD), sol-gel synthesis, plasma-enhanced pulsed laser deposition, and the template method. [98, 123-125] Zhang et al. [126] explored CVD in preparing MXene-MoS<sub>2</sub> nanocomposites and obtained a well-structured composite material with metallic properties and an excellent electrochemical performance of  $\sim 69$  mV at a current density of  $10 \text{ mA}\cdot\text{cm}^{-2}$ . The CVD method was also explored by Wang et al. [127] to manufacture carbide and nitride MXenes directly without MAX phases. In the experiment, as posited by the authors, the MXenes were developed at  $950^\circ\text{C}$  on a titanium surface with a mixture of Methane ( $\text{CH}_4$ ) and Titanium tetrachloride ( $\text{TiCl}_4$ ) gas diluted in Argon (Ar). This was followed by exposure of the synthesized product (CVD- $\text{Ti}_2\text{CCl}_2$ ) for 15 minutes. The resulting MXenes are reported to have excellent features for energy storage in Li-ion intercalation. Again, scholars such as Joshi et al. [128] used the CVD approach to effectively manufacture molybdenum nitride by synthesizing the precursor material ( $\text{MoO}_3$ ) for insertion electrodes in  $\text{Li}^+$  batteries. Gogotsi [124] also reports a successful synthesis of thin  $\text{Mo}_2\text{C}$  crystals in a study to expand the scope of 2D materials with innovative methods.

Besides the CVD method of MXene synthesis using the bottom-up approach, a recent study explored the template method to effectively produce  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene with a remarkable electrical conductivity of up to  $11,000 \text{ S cm}^{-1}$  and an excellent breakdown current density of  $1.2 \times 10^8 \text{ A cm}^{-2}$ . [129] Another approach to the bottom-up synthesis of MXenes is the use of the PVD technique, which is reported to perform between  $700^\circ\text{C}$  and  $1000^\circ\text{C}$ . [130, 131]

Pyrolysis and molten salt synthesis are other approaches that have also gained attention using the bottom-up method. [100] With the pyrolysis approach, Wang et al. [132] designed  $\text{Mo}_2\text{C}/\text{C}$  composites with Mo-substituted ZIF-8 (Mo/ZIF-8) for high-performance microwave absorption. The composite material exhibited excellent microwave absorption over a frequency range of 2.0-18.0 GHz. Also, Chen et al. [133] successfully used the molten salt approach to synthesize several MXene types such as  $\text{Ti}_3\text{C}_2\text{T}_x$ ,  $\text{Ti}_2\text{CT}_x$ ,  $\text{Ti}_3\text{CNT}_x$ , and  $\text{Ti}_4\text{N}_3\text{T}_x$ . The authors reported on the synthesis of the MXenes in the open air with the aforementioned approach in the quest to reduce environmental hazards associated with MXene production and to ensure a low-cost method of MXene synthesis. Moreover, Cheng et al. [134] report the use of the molten salt approach in developing a catalyst comprising molybdenum carbide nanodots

and carbon nanosheets ( $\text{Mo}_2\text{C}/\text{C}$ ) composite. The  $\text{Mo}_2\text{C}/\text{C}$  composite material, as reported in the study, exhibited excellent performance with an  $\text{NH}_3$  yield rate of  $11.3 \mu\text{g h}^{-1} \text{mg}^{-1} \text{Mo}_2\text{C}$  and Faradic efficiency of 7.8% for nitrogen reduction reaction under ambient conditions.

**Figure 7** shows an illustration of the molten salt method used to manufacture the  $\text{Mo}_2\text{C}/\text{C}$  nanosheet using the bottom-up approach to material synthesis.

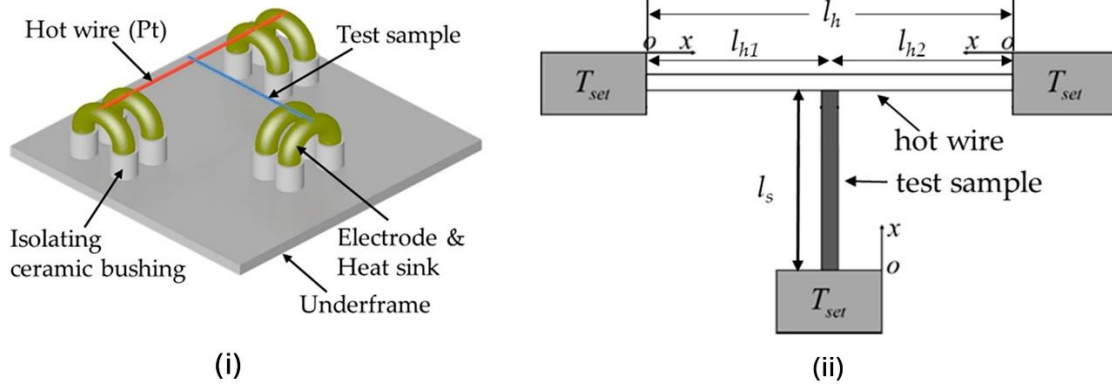


**Figure 7:** Bottom-up approach to material synthesis with molten salt method from the literature. (a) Schematic illustration of  $\text{Mo}_2\text{C}/\text{C}$  composite material synthesis for catalyst performance. (b-d) SEM, AFM, and TEM images of the  $\text{Mo}_2\text{C}/\text{C}$  composite material. (e) HRTEM image of the  $\text{Mo}_2\text{C}/\text{C}$  material. The corresponding Fast-Fourier-transform pattern is embedded in the top right corner of (e). (f-h) STEM image of the  $\text{Mo}_2\text{C}/\text{C}$  nanosheets and the corresponding EDS mapping. Reprinted from Cheng et al.<sup>[134]</sup> with permission: © 2018 Wiley-VCH.

#### 4. Estimating the Effective Conductivity of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-integrated Textiles

There are a variety of methods for determining the conductivity of textiles manufactured with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes, which are based on techniques developed for other materials. For instance, textile fibers enhanced with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes could be subjected to the steady-state T-type method adopted by Chen et al.<sup>[135]</sup> to measure the thermal/electrical conductivity of  $\text{Ti}_3\text{C}_2\text{T}_x$  composite samples, as shown in **Figure 8**. In this case, both ends of a platinum wire (a heating element) were connected to copper electrodes isolated with ceramic bushings fixed on a metal underframe to serve as a support. With the help of silver gel, one end of the sample was connected to the middle of the platinum wire, and the other was connected to the copper electrode. To reduce heat loss, the setup was placed in a vacuum chamber and maintained at a pressure below  $10^{-4}$  Pa with the help of mechanical and molecular pumps. To measure the electrical and thermal conductive effectiveness of the sample, four significant components are needed to form the circuit: a constant voltage source, a standard resistor, a hot wire, and a test sample (in this case, the  $\text{Ti}_3\text{C}_2\text{T}_x$ /textile material composite). The thermal conductivity, denoted by  $\lambda_s$ , was then measured with equation (1) described in previous studies.<sup>[135, 136]</sup> From the formula,  $L_s$  represents the length of the composite material under test between two connecting ends, and  $L_h$  is the length of the platinum (hot wire). The cross-sectional areas of the platinum wire and the test sample are denoted by  $A_h$  and  $A_s$ , respectively. The thermal conductivity of the hot wire (platinum) is represented by  $\lambda_h$ ,  $qv$  indicates the heat generation rate of the platinum wire, and  $\Delta T_v$  represents the average temperature increase of the platinum wire per unit volume.

$$\lambda_s = \frac{L_s L_h \lambda_h A_h (L_h^3 qv - 12 L_h \lambda_h \Delta T_v)}{L_{h1} L_{h2} A_s [12 L_h \lambda_h \Delta T_v - qv (L_{h1}^3 + L_{h2}^3)]} \quad (1)$$



**Figure 8:** Schematic illustration of the T-typed method of thermal and electric conductivity measurement. (i) Illustration of the sample connection. (ii) The physical model. Reprinted from Chen et al. <sup>[135]</sup>

To test the electrical conductivity of composite materials, Taherian developed a model that incorporates material features such as filler aspect ratio, wettability, filler electrical conductivity, matrix conductivity, and filler roundness using the sigmoidal equation to capture the percolation threshold phenomenon.<sup>[137]</sup> The sigmoidal formula shown in equation (2) has  $f(x)$  as the electrical conductivity of the composite material, with  $x$  representing the filler volume fraction.  $y_0$  denotes the baseline conductivity,  $a$  represents the maximum possible of the relevant conductivity mechanism,  $b$  controls the steepness of the transition,  $c$  shifts the curve, and  $x_0$  is the percolation threshold. The final model developed for the electrical conductivity test is shown in equation (3). The equation has  $\sigma_{composite}$  as a dependent variable, indicating the effective conductivity of the composite material,  $\sigma_m$  represents the conductivity of the matrix without filler,  $a_o$  denotes a scaling factor,  $AR$  stands for the aspect ratio,  $\sigma_f$  represents the electrical conductivity of the filler,  $b$  shows the steepness of the transition,  $x$  indicates the volume fraction of the filler, *roundness* shows the shape of the filler particles, and  $\cos\theta$  represents the alignment of the filler particles. As a validated equation for modeling the effective conductivity of composite materials,<sup>[137]</sup> its adaptation in assessing the effective conductivity of  $Ti_3C_2T_x$  MXenes-integrated textile will provide reliable results when manufacturing and testing biomedical sensors and other devices.

$$f(x) = y_0 + \frac{a}{c + \exp\left(\frac{-(x - x_0)}{b}\right)} \quad (2)$$

$$\sigma_{composite} = \sigma_m + \frac{a_o \cdot (AR)(\sigma_f)}{1 + b \cdot \exp \left[ -\frac{(x - roundness)}{\cos \theta} \right]} \quad (3)$$

## 5. Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-integrated Textiles

Embedding 2D materials, including MXenes, in smart textiles has caused significant advancement in the textile industry. MXenes are known for their accurate sensing and energy storage abilities, especially when embedded in textiles for biomedical applications.<sup>[138-140]</sup> Fibers, yarns, textiles, and composites could be enhanced with MXenes to add functionality. It is established that Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene can bond well with polymer-based textiles that are polar-structured and maintain the electrical conductivity property of such textiles.<sup>[141]</sup> The qualities of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-based textiles include surface-enhanced, highly conductive, and stretchable properties that could be obtained even through a wet-spinning process for sensor manufacturing.<sup>[142]</sup> With excellent mechanical properties, high sensitivity, quick sensor response times, flexibility, good conformity, and stability properties of MXene-based sensors, other nanomaterials such as CNTs, graphene, and other metal nanostructures are gradually being replaced in smart textiles in many cases due to their drawbacks such as uncontrolled cracks, low electrical conductivity, and high cost of manufacturing.<sup>[143, 144]</sup> Recently, a highly robust electromagnetic interference shield was designed using a composite of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene, a carbon-based fabric, and thermoplastic polyurethane.<sup>[145]</sup> The composite material is reported to have an improved tensile strength of 170.2 MPa, an increased MXene fraction, shielding effectiveness of 40.4dB, excellent flexibility, and resistance stability. While the developed textile was created for electromagnetic interference shielding applications, however, the processes could be applied to create other MXene-based E-textiles. The procedures followed to manufacture the fabric, the electrohydrodynamic atomization deposition, and the chemical reactions on the surface of the fabric are presented in Figure 9a-Figure 9c. In Figure 9a, the Carbon-fiber fabric was treated by immersing it in acetone reflux for 24 hours, followed by washing in deionized water and drying. This was followed by layer-by-layer stacking and hot pressing for 25 minutes under 180°C to obtain the composite textile material. In Figure 9b, the Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene was atomized on both sides of the fabric, and the chemical reactions on the fabric's surface are illustrated in Figure 9c. Mxene-based fabric for flexible sensors in smart textiles ensures remarkable progress in wearable electronics for health monitoring. A superhydrophobic smart fabric decorated with Mxene is reported to be a potential candidate for smart wearable electronics for medical

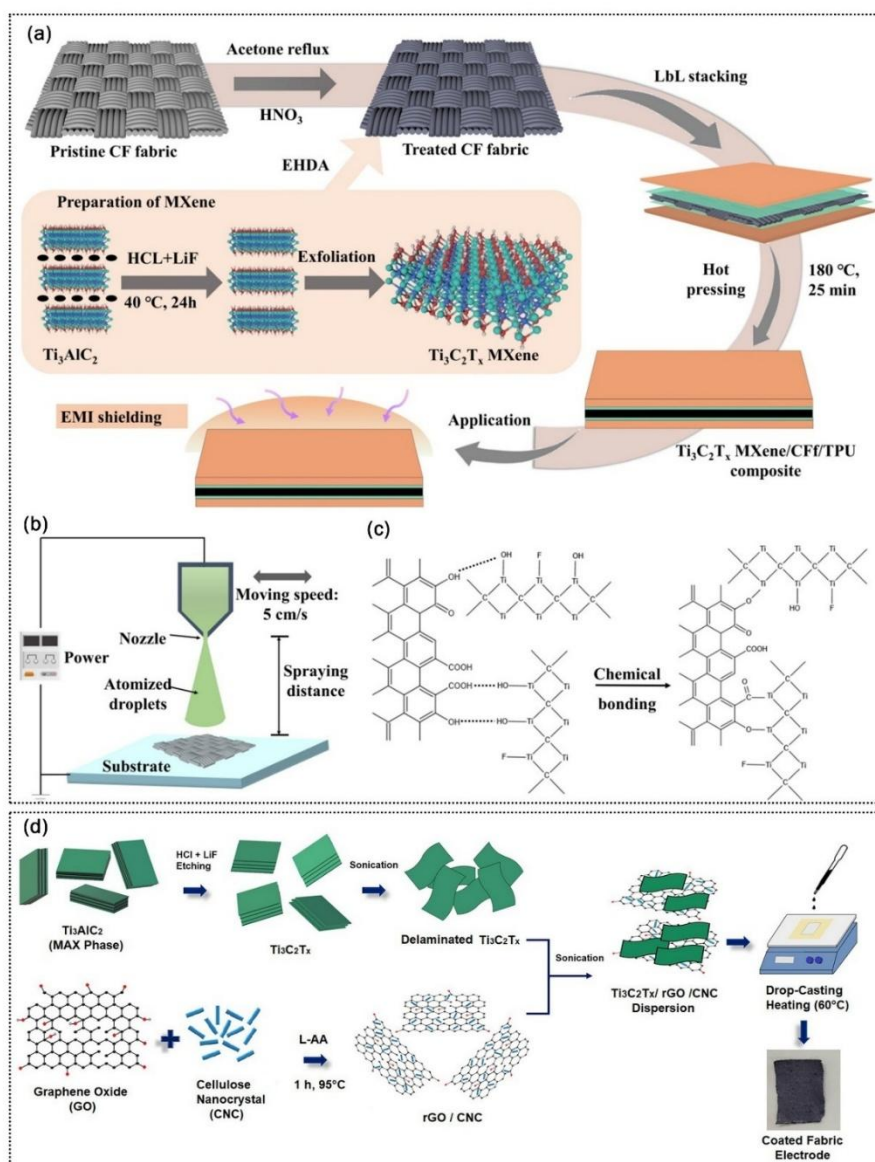
applications.<sup>[146]</sup> The MXene-integrated textile was manufactured from nylon fabric using MXene as the main conducting material, modified with polydopamine, and sprayed with Silicon dioxide (SiO<sub>2</sub>) and FOTS as hydrophobic materials. Findings indicate that the superhydrophobic and highly conductive smart fabric can monitor breathing, block electromagnetic waves, and generate heat due to the MXene component integrated. An improved sensing performance is also observed with 0.2% strain detection, a fast response time of 60 ms, a quick recovery time of 90 ms, and a stability of 5000 stretching cycles. Also, a highly stable and sensitive smart glove is manufactured using MXene-based textile sensors for adaptive gesture recognition.<sup>[147]</sup> With the Mxene content, the smart glove showed higher sensitivity, stronger and more stable mechanical-electrical performance, and better signal consistency. It is reported that the glove showed high accuracy of up to 99.5% for gesture recognition and maintained excellent performance of 98.1% upon being expanded to more gestures.<sup>[147]</sup> In addition, He et al.<sup>[148]</sup> manufactured highly conductive and photothermal cotton yarns by coating with Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene nanosheet and poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS) composite, forming a core-shell structure. The MXene-based yarn showed excellent electrical conductivity of 21.8 Ω cm<sup>-1</sup>, quick electrothermal response, and excellent photothermal conversion. The composite yarn was further knitted to produce sensors capable of monitoring human movements and health signals with improved performance in sensitivity and durability. Moreover, in a study investigating appropriate methodologies and factors that help MXenes bond firmly to fabric surfaces in smart textiles for biomedical applications, Liu et al.<sup>[149]</sup> produced a MXene-integrated cotton fabric that could withstand washing and be used as a smart wearable for pressure sensing. The textile pressure sensor exhibited excellent properties, including a high gauge factor of 7.67 kPa<sup>-1</sup>, a quick response/relaxation speed of <35 ms, and incredible stability over >2000 loading and unloading cycles. Zhao et al.<sup>[150]</sup> reported the production of a Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-integrated multifunctional fabric created from a nonwoven fabric made from cellulose, which was used to create a wearable respiration monitor. Here, the MXene textile acted as a moisture sensor, where the dynamic changes in moisture levels due to breathing could be tracked.

Yu et al.<sup>[151]</sup> have reported wearable piezoelectric pressure sensors obtained from Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-integrated nonwoven fabric. The Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-integrated nonwoven fabric exhibited excellent durability to cyclic bending (500 cycles) and abrasion (2000 cycles). The sensors had a high sensitivity of 6.31 kPa<sup>-1</sup>, were durable and functioned correctly after 2000 loading-unloading cycles, could sense pressures of up to 150kPa, and had a response time of

300 ms/260 ms. The  $\text{Ti}_3\text{C}_2\text{T}_x$  and nonwoven composite textile, therefore, exhibited excellent properties and offered a good prospect for wearable sensors for health monitoring applications. Power supplies are also critical for any wearable device, such as those intended for healthcare applications. In the interest of producing a wearable power supply, the properties of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene have recently been explored by Duygun and Bedeloğlu to produce a high-performance cotton fabric for textile-based electrodes in wearable supercapacitors.<sup>[152]</sup> In this process, reduced graphene oxide was synthesized together with cellulose nanocrystals in addition to the preparation of a dispersion composed of  $\text{Ti}_3\text{C}_2\text{T}_x$ , reduced graphene oxide, and cellulose nanocrystals at varied ratios of 5% wt., 15% wt., 30% wt., and 50% wt. rGO/CNC content. This was followed by coating a plain-woven cotton fabric with various dispersions prepared using the drop-casting technique. The resulting  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated fabric showed high capacitance ( $501.1 \text{ F g}^{-1}$ ) at  $0.3 \text{ A g}^{-1}$  current density, good electrochemical stability, and low internal electrode resistance. **Figure 9d** shows a schematic illustration of the  $\text{Ti}_3\text{C}_2\text{T}_x$  and  $\text{Ti}_3\text{C}_2\text{T}_x/\text{rGO/CNC}$  dispersion preparation and drop-casting of cotton fabric. Several other scholars have also reported  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated textile inventions.<sup>[153-156]</sup> It could be deduced from previous studies that integrating  $\text{Ti}_3\text{C}_2\text{T}_x$  with textile materials has increased the performance of textiles and widened the scope of textile science and engineering. In this vein, MXene-integrated textiles have gained application in other areas, including Electromagnetic Interference (EMI) shielding, electrical heating, energy storage, etc.

Regarding the EMI shielding and heating capabilities of MXene-integrated textiles, it is reported in a previous study that a MXene-decorated nylon fabric showed excellent EMI shielding of 66.5 dB in X-band and electrothermal heating of  $102.3^\circ\text{C}$  at 8V.<sup>[146]</sup> Again, Yan et al. manufactured an MXene-based textile by forming a highly antioxidative MXene@gallic acid composite and using metal ions ( $\text{Fe}^{3+}$ ) to cross-link the manufactured composite onto a carboxylated cotton fabric through covalent bonding.<sup>[157]</sup> The MXene-enhanced cotton fabric exhibited improved performance, high electrical conductivity of  $\sim 330 \text{ S/m}$ , remarkable photothermal convertibility, and good infrared thermal camouflage properties. Particularly, the MXene-based textile showed a high EMI shielding efficiency of  $\sim 35 \text{ dB}$ , making it suitable for application in products that require blocking or reducing electromagnetic waves, such as wearable electronics, personal protective clothing, military and defense wearables, etc. Moreover, Feng et al. developed core-sheath fibers with MXene as the core and CNTs as the sheath using the wet spinning method.<sup>[158]</sup> The MXene-based fabric exhibited EMI shielding effectiveness of 23.40 dB and absorption coefficient of 0.63, making it appropriate

for smart textiles. Aside from EMI shielding and heating applications, MXene-integrated textiles perform incredibly in energy storage. A study on wearable energy storage devices posits that  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based textile supercapacitors exhibit enhanced areal and volumetric capacitance compared with textile supercapacitors without MXene content.<sup>[21]</sup> Also, Zhang et al.<sup>[159]</sup> designed a  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based textile supercapacitor with hierarchical spacer fabrics as a skeleton for mechanical support and stable performance, while  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene served as a current collector and active material for the supercapacitor. The resulting MXene-based textile supercapacitor showed a remarkable areal capacitance of  $415 \text{ mF cm}^{-2}$  with a MXene loading of  $4.2 \text{ mg cm}^{-2}$ , making it suitable for energy storage in wearable devices for healthcare applications. It is worth noting that MXene-based conductive textiles are applied in several areas due to their improved qualities provided by the MXene content.

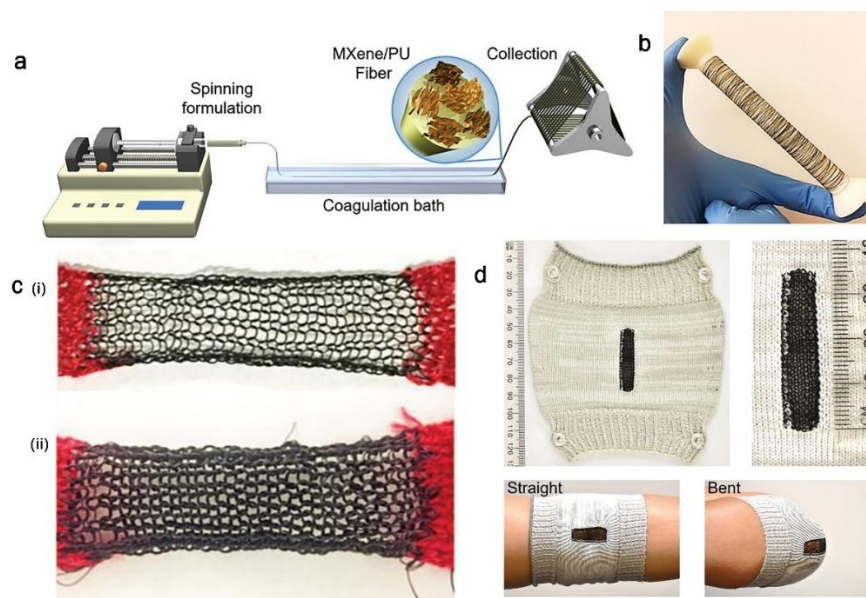


**Figure 9:** Manufacturing and reaction of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene/carbon fiber fabric/thermoplastic polyurethane composite material from the literature. (a) Illustration of the preparation process for the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based textile. (b) Illustration of the electrohydrodynamic atomization deposition. (c) The chemical reactions on the surface of the fabric. Reprinted from Duan, et al.<sup>[145]</sup> with permission: © 2022 Elsevier. (d) A schematic illustration of the  $\text{Ti}_3\text{C}_2\text{T}_x$  and  $\text{Ti}_3\text{C}_2\text{T}_x/\text{rGO}/\text{CNC}$  dispersion preparation and drop-casting of cotton fabric. Reprinted from Duygun and Bedeloğlu.<sup>[152]</sup>

## 6. The Role of $\text{Ti}_3\text{C}_2\text{T}_x$ MXene in Conductive Textiles for Wearable Applications

As discussed earlier, the unique properties of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes make them useful for conductive textile manufacturing.<sup>[35, 36]</sup> Conductive textiles have previously been obtained from conductive polymer materials such as polythiophene, polyaniline, and polypyrrole.<sup>[160, 161]</sup> However, these are not ideal for certain applications as they can have insufficient conductivity, environmental instability, and a lack of robustness and mechanical strength.<sup>[162]</sup> MXenes, as a 2D material, can overcome these shortcomings and have mostly been complemented with polymers in conductive textile material manufacturing after their discovery in the past few years.<sup>[154, 163, 164]</sup>  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene is not only useful in its ability to transfer electrical charges in sensors, but it can also act as an electro-catalyst by engaging in electrochemical reactions in the sensing process; this can be especially useful for wearable electronics.<sup>[165]</sup> Seyedin, et al.<sup>[142]</sup> proved the significant role that  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes can play in achieving a highly conductive and stretchable textile using a scalable wet-spinning process. To enrich the conductivity and mechanical properties of the polyurethane, the authors introduced  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes to form a composite fiber that could undergo knitting for strain sensor manufacturing, as presented in **Figure 10**. From **Figure 10a**, the wet-spinning technique for  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene/polyurethane composite fiber manufacturing is illustrated, with the resulting composite yarn shown in **Figure 10b**. A fabric knitted using the yarn is shown in **Figure 10c**, with (i) single and (ii) four-ply of the MXene-based yarn. Again, the four-ply yarn knitted fabric and its straight and bent conditions at the elbow are shown in **Figure 10d**. Interestingly, impregnating textiles with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes provided a three-dimensional structure of an evenly distributed network of conductivity across the surface of the textile material.<sup>[166]</sup> With inspiration from Zhang et al.<sup>[166]</sup> and the findings from Zou et al.<sup>[167]</sup>, the scalable fabrication of composite yarns incorporated with MXene promises enhanced flexible wearable intelligent textiles for healthcare applications. For instance, a composite of MXene, cotton, and spandex (MCSY) yields flexible, strong, and comfortable composite textiles,

which could be mass-produced with simple dipping and drying techniques. As posited by Zou et al.<sup>[167]</sup>, the MCSY yarn is enhanced with mechanical properties for human motion monitoring due to the presence of the Mxene.



**Figure 10:** Illustration of a MXene-based textile manufactured for sensing application from the literature. (a) Schematic illustration of the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene/polyurethane composite fiber spinning process (b) Photograph of the spun MXene-based fiber. (c) A single jersey knitted fabric with (i) single and (ii) four-ply yarn of the MXene-based fiber. (d) The four-ply yarn knitted fabric and its straight and bent conditions at the elbow with an embedded strain sensor. Reprinted from Seyedin, et al.<sup>[142]</sup> with permission: © 2020 Wiley-VCH.

Buttressing the incredible role of MXenes in conductive textiles for wearable electronics, Shi et al.<sup>[153]</sup> revealed the application of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes in energy-free passive radiative heating systems precisely for the human body due to their low mid-infrared radiative emissivity features. This was explored by decorating a nanoporous polyethylene textile with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes for body heating applications. It should be noted that the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes improved the conductivity of the textile to carry out its heating performance indoors and outdoors. Also, Ma et al.<sup>[168]</sup> demonstrated the importance of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes in producing a hydrophobic and multifunctional textile composite for thermal control and human motion detection, where it served as a conductive and multifunctional active material. With the presence of the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes, the study reported a smart textile that exhibited high equilibrium temperatures of 104.9 and 118.7 °C under low power illumination of 1.25 W cm<sup>-2</sup> and a 4V

working voltage. The textile, when used to manufacture a wearable pressure sensor, showed high sensitivity and a quick response time of 30- 40ms.

It is established that the electrical conductivity and large surface area of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes make them useful materials in supercapacitors and batteries, coupled with their role as catalysts in hydrogen evolution and carbon dioxide reduction.<sup>[169, 170]</sup> This shows the multifunctional roles played by  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes in wearable textile technology. Regarding its multifunctional performance and exceptional characteristics, Yu et al.<sup>[151]</sup> found  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene as the best surface embellishment material among other MXene types such as  $\text{Ti}_2\text{CT}_x$ ,  $\text{Ti}_3\text{CNT}_x$ ,  $\text{Mo}_2\text{CT}_x$ ,  $\text{Nb}_2\text{CT}_x$ , and  $\text{Mo}_2\text{TiC}_2\text{T}$ , for textile-based biomedical sensors. Also, the compatibility of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene with other functional materials has led to it playing a key role as a composite material with different materials such as graphene, carbon, polyaniline, and nanosheets-silver nanowire for functional applications.<sup>[171-174]</sup> For instance, Zheng et al.<sup>[175]</sup> combined  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene with reduced graphene oxide to manufacture a multifunctional textile that can store electrochemical energy, detect human motion, and be used for electromagnetic interference shielding. The good compatibility of the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene and the reduced graphene oxide resulted in a supercapacitor with high capacitances of  $383.3 \text{ F g}^{-1}$  ( $258 \text{ mF cm}^{-2}$ ). Again, Liu et al.<sup>[176]</sup> manufactured core-shell fibers with regenerated cellulose that possess an excellent strength of 134.7 MPa, a high toughness of  $14.1 \text{ MJ m}^{-3}$ , a large elongation before breaking (13%), and a high conductivity of  $2.37 \times 10^3 \text{ S m}^{-1}$ , thanks to the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene component of the composite material. It could be said that the incredible role of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene in conductive textile manufacturing shows a promising future for its use in wearable applications, especially in the health sector, as expounded in past studies presented in the review.

## 7. $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-integrated Sensors

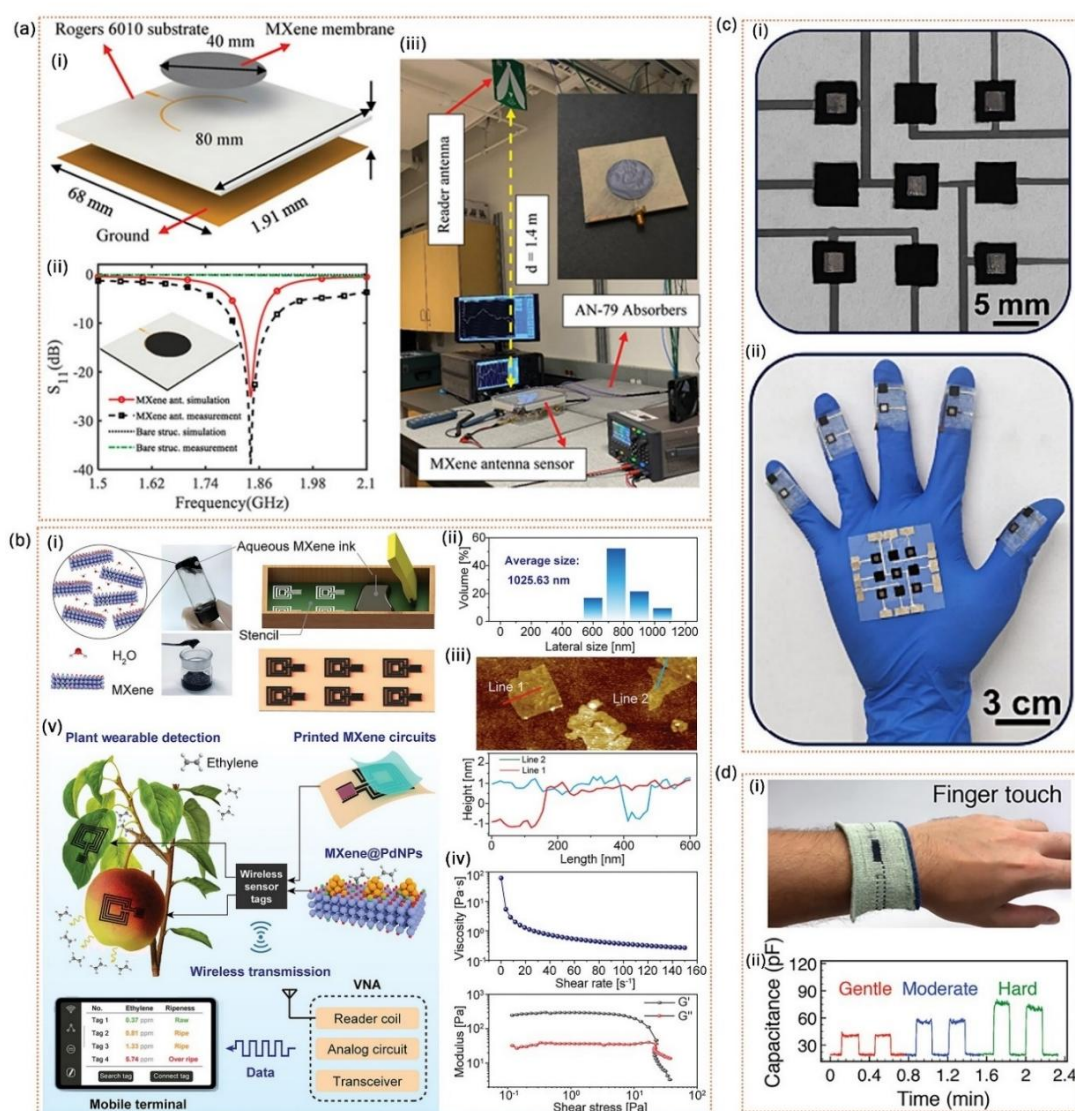
With the rise in wearable electronics and intelligent systems, sensors have become invaluable devices for successfully implementing concepts.<sup>[177]</sup> Sensors are particularly valuable in the healthcare setting, as monitoring patients can be critical for correct diagnosis and treatment.  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes open an opportunity for producing advanced sensors for wearable applications, especially in textile-based wearables for health monitoring. It is established that sensor manufacturing is one area that is expected to see massive improvement with the advent of MXenes.<sup>[178]</sup> Mathew and Rout suggest that MXenes are widely used in electrochemical biosensors over other 2D nanomaterials due to their desirable properties for such sensors, including hydrophilicity, high electron transfer capacity, large surface area, and easier surface

modification<sup>[179]</sup> Further, Ta et al.<sup>[180]</sup> single out  $\text{Ti}_3\text{C}_2\text{T}_x$  as an exceptional type of MXene when applied widely in product design, especially in gas sensing and energy harvesting devices. Following this, Zhang et al.<sup>[166]</sup> presented a textile-based flexible sensor manufactured from  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene and Polyethylene Terephthalate (PET) composites for pulse monitoring applications. This was achieved by the impregnation method, where a thin film of the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes was held firmly onto the surface of the fibers, imparting conductivity properties to the textile. The  $\text{Ti}_3\text{C}_2\text{T}_x$ /PET integrated textile sensor, after testing, exhibited excellent features such as a high sensitivity of  $35 \text{ kPa}^{-1}$ , a wide response range of 0-40 kPa, a fast response time of 45 ms, and excellent stability of more than 2000 loading and unloading cycles. Chen et al.<sup>[181]</sup> experimented with integrating  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes with fiber optic biosensors and concluded that the resulting sensor demonstrated a 30% boost, which indicated a successful increment of sensitivity with the help of the  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes. Also, Waheed et al.<sup>[182]</sup> manufactured a humidity sensor with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene nanosheets and graphene oxide serving as electrodes and sensing layers, respectively. It was reported that the sensors exhibited excellent characteristics such as a 6%-97% response range at 1 kHz and 10 kHz frequencies, 0.8s response time, 0.9s recovery time, and maintained uninterrupted performance for over 24h.

In a study to explore multifunctional sensor manufacturing, Gao et al.<sup>[183]</sup> designed a skin-like sensor to detect and distinguish temperature and pressure stimuli. In the experiment process,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene was integrated with elastic and porous substrates to increase their thermoelectric and conducting properties for effective sensing. Hosseini-Shokouh et al.<sup>[184]</sup> also designed  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated sensors for hydrogen sulfide ( $\text{H}_2\text{S}$ ) sensing and concluded in their study the unique performance of the sensor due to the presence of the MXene. Another account is given on an impedance-type humidity sensor manufactured with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes and graphitic carbon nitride ( $\text{g-C}_3\text{N}_4$ ) composites, which were explored on a PET substrate.<sup>[185]</sup> The composite nanomaterials of which  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene formed an integral part produced a sensor with a high response and recovery time.

As detailed above,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene has been used in a variety of sensor designs for several applications. Further examples include  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated sensor with high sensitivity and exceptional selectivity to ammonia gas at room temperature,<sup>[186]</sup> a textile-based humidity sensor designed by coating MXene and multi-walled carbon nanotubes, which was reported to have exhibited 265% response at 90% relative humidity,<sup>[187]</sup> breathable and waterproof MXene-integrated textiles with a conductive network for strain and temperature sensing applications,<sup>[188]</sup>  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene and protein composites for a wearable, breathable, and

degradable sensor designed for pressure monitoring applications,<sup>[189]</sup> and  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based gas sensors with a detection limit of 50-100 parts per billion for volatile organic compound gases at room temperature.<sup>[190]</sup> **Figure 11** shows sample sensors developed from  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes for various applications. Also, Table 1 presents the various MXene-integrated sensors, their application, and the brains behind the inventions.



**Figure 11:**  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated sensors. (a)  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based volatile organic compounds and humidity sensing antenna. (i) Schematic illustration and dimensions of the MXene-based antenna sensor. (ii) The simulation and measurement results of the structure with and without MXene membrane. (iii) The measurement setup for the MXene-based antenna sensor. Reprinted from Kazemi et al.<sup>[191]</sup> with permission: © 2022 Wiley-VCH. (b) Fully-MXene-printed wearable sensor tags for wireless ethylene detection in plants. (i) MXene-based aqueous ink designed for screen printing. (ii) Lateral size distribution of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene

nanoflakes. (iii) AFM image of exfoliated MXene nanoflakes. (iv) Viscosity plotted as a function of shear rates (top), storage modulus ( $G'$ ) and loss modulus ( $G''$ ) plotted as a function of shear stress (bottom). (v) Schematic illustration of the fully-MXene-printed wearable sensor for wireless ethylene detection in plants. Reprinted from Li, et al.<sup>[192]</sup> with permission: © 2023 Wiley-VCH. (c)  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based dual-mode sensor for pressure and temperature detection. (i) Photograph of the sensor display. (ii) Photograph of a glove embedded with five dual-mode sensors and a  $3 \times 3$  dual-mode sensor array. Reprinted from Yuan et al.<sup>[193]</sup> with permission: © 2024 Elsevier. (d) Capacitive knitted pressure sensor device designed out of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene. (i) Photograph of the knitted pressure sensor button with an active area of  $16 \text{ mm} \times 5 \text{ mm}$ . (ii) Capacitance output of the sensor when a gentle, moderate, or hard pressure is applied to the device by a finger. Reprinted from Uzun et al.<sup>[194]</sup> with permission: © 2019 Wiley-VCH.

**Table 1:** Summary of Mxene-integrated sensors, their application, and the authors behind their manufacturing

| Authors                                  | MXene-integrated sensors                                                  | Application                                                          |
|------------------------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------|
| Kim, et al. <sup>[190]</sup>             | A solid-state gas sensor                                                  | For detecting volatile organic compounds                             |
| Chen, et al. <sup>[181]</sup>            | Refractive index sensor                                                   | For trace biochemical molecule detection                             |
| Yao, et al. <sup>[186]</sup>             | Ammonia ( $\text{NH}_3$ ) gas sensor                                      | For detecting $\text{NH}_3$ gas at room temperature                  |
| Luo J. , et al. <sup>[188]</sup>         | A multifunctional wearable textile sensor                                 | For strain and temperature sensing application                       |
| Chao, et al. <sup>[189]</sup>            | A breathable and degradable pressure sensor                               | Used for pressure monitoring                                         |
| Xing, et al. <sup>[187]</sup>            | Humidity sensor                                                           | For real-time respiration monitoring                                 |
| Zhang, et al. <sup>[166]</sup>           | $\text{Ti}_3\text{C}_2\text{T}_x$ /PET integrated flexible textile sensor | For pulse monitoring applications                                    |
| Gao, et al. <sup>[183]</sup>             | A skin-like Mxene-integrated sensor                                       | For temperature and pressure sensing                                 |
| Hosseini-Shokouh et al. <sup>[184]</sup> | Hydrogen sulfide ( $\text{H}_2\text{S}$ ) sensor                          | Applied in $\text{H}_2\text{S}$ gas sensing                          |
| Lu et al. <sup>[185]</sup>               | Flexible impedance sensor                                                 | Humidity-sensing applications                                        |
| Waheed, et al. <sup>[182]</sup>          | Humidity sensor                                                           | Used for non-contact proximity sensing and human breathing detection |

## 8. Key Findings and Future Perspectives

Textiles can be enhanced with advanced materials to enrich their performance and create devices, such as sensors, for use in various areas, including the health sector. Among these advanced materials is  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene, which researchers have extensively employed for a diverse range of applications due to specific desirable properties such as its energy storage

ability, good hydrophilicity, excellent mechanical strength, good electrical conductivity, large surface area, and good transparency. Amongst the many possible applications of the material, this makes it suitable for biomedical sensor manufacturing for health monitoring. It is established that  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes-integrated textiles occupy a useful position in sensor manufacturing for monitoring human physiological vitals such as temperature, pressure, strain, heart pulse, glucose, and lactate. It is also observed that several advancements have been made regarding the synthesis of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene. The two widely used approaches for MXene synthesis are the top-down and bottom-up methods, with many concerns raised about the environmental hazards caused by the former, although it is praised for yielding high-quality and sizeable flakes. This has led to scholars such as Naguib et al.<sup>[13]</sup> recommending the use of  $\text{LiF-HCl}$  as an alternative solution to boost the production of MXenes in regions where  $\text{HF}$  is not allowed in laboratories due to its harmful nature. Advances in production, such as those by Chen et al.<sup>[133]</sup>, where MXenes were produced in the open air, show the potential for the production process to be simplified, reducing both risk and cost.

Textiles are one of the best materials to be integrated with smart devices such as sensors for biomedical applications due to their flexibility, comfort, durability, and ability to withstand washing. These properties also make textiles good candidates for integrating with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene.  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated textiles possess surface-enhanced, highly conductive, and stretchable properties that could be obtained even through a wet-spinning process for sensor manufacturing. Also, as found in the study, sensors developed out of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes have excellent mechanical properties, high sensitivity, quick response, flexibility, good conformity, and are stable. This has resulted in scholars including Zhang et al.,<sup>[166]</sup> Chen et al.,<sup>[181]</sup> Waheed et al.,<sup>[182]</sup> and Gao et al.<sup>[183]</sup> incorporating  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene into sensor designs. To estimate the effective electrical conductivity of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-based textiles, the study discovered suitable approaches, such as the steady-state T-type method of measuring the conductivity of composite materials<sup>[135]</sup> and a model developed by Taherian<sup>[137]</sup> out of the sigmoidal equation. These models were used to successfully measure the conductivity of composite materials as found in the study.

Moreover, the study found that  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes can play a crucial role in producing conductive textiles and overcoming the shortcomings of insufficient conductivity, environmental instability, lack of robustness, and mechanical strength seen in other conductive polymer materials such as polythiophene, polyaniline, and polypyrrole. Also,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene not only serves its significant function of transferring electrical charges in sensors but also acts as an electro-catalyst by engaging in electrochemical reactions in the

sensing process, which is especially useful for wearable electronics. The study has demonstrated that biomedical sensors have been designed purposely to detect and deliver information about patients for onward acquisition and processing by healthcare professionals for smart healthcare delivery. Biosensors are indispensable devices for the delivery of smart healthcare.

From the findings, a more sustainable approach to MXene synthesis should be deeply rooted in future research to eliminate the hazardous processes involved, especially in the traditional top-down approach. As  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes are promising materials for wearable electronics, devising appropriate methodologies that are harmless to the environment and human health would take the use of MXenes for wearable technology further. Also, the ability to enhance textiles with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes for smart applications calls for scholars to focus on textile-based sensors, as they have desirable features such as flexibility, mechanical strength, and comfort needed in wearable devices, especially for biomedical purposes, as compared to traditional electronic devices that are more rigid and lack comfort. Moreover, developing standardized models purposely for measuring the conductivity of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes-based textiles could be addressed in future studies, although the sigmoidal and T-type methods are appropriate models. These models could be refined and validated in several ways to improve their application in wearable textile device design. Lastly, future studies could explore the integration of MXene-based biosensors into the IoT to allow continuous monitoring of patient health and seamless data collection and analysis for improved healthcare delivery.

## 9. Conclusion

This review delved into the literature related to applying  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes with textiles for biomedical sensor development by reviewing key thematic areas such as the synthesis/characterization of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes,  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated textiles, effective conductivity estimation, the role of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes in conductive textile manufacturing, and biomedical sensors. Findings revealed that  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes are promising materials in advancing wearable textile electronics, especially for sensor development.  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes-integrated sensors can monitor various important human physiological vitals such as temperature, pressure, strain, heart pulse, glucose, and lactate. The feasibility of using  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes in conductive textile manufacturing using technologies such as wet-spinning promises scalable production of MXene-integrated smart textiles for advanced healthcare delivery. Sustainability concerns regarding MXene-synthesis may call for using LiF-HCl in the synthesis when using the top-down approach to produce high-quality MXenes. Future

research to unearth sustainable approaches to MXene synthesis, improvement of bio-compatibility, durability, and the integration of IoT into MXene-integrated textiles would expand their application in wearable electronics for healthcare delivery.

### **Author contributions**

George Kwame Fobiri took the lead in conceptualization, formal analysis, investigation, and drafting the original manuscript; also contributed equally to reviewing and editing. Ebenezer Kofi Howard led the conceptualization alongside Fobiri, supported the original drafting, supervised the work, and equally contributed to reviewing and editing. Timothy Crentsil contributed equally to the conceptualization, supervision, and review/editing of the manuscript. Charles Frimpong also played an equal role in conceptualization, supervision, and reviewing/editing the manuscript. Theo Hughes-Riley contributed equally to conceptualization and original drafting, and took the lead in reviewing and editing the manuscript.

### **Acknowledgements**

No financial support was received for this research

### **Conflict of Interest Statement**

The authors declare no conflict of interest.

### **Data Availability Statement**

N/A

Received: ((will be filled in by the editorial staff))

Revised: ((will be filled in by the editorial staff))

Published online: ((will be filled in by the editorial staff))

## References

- [1] J. S. Meena, S. B. Choi, S.-B. Jung, and J.-W. Kim, "Electronic textiles: New age of wearable technology for healthcare and fitness solutions," *Materials Today Bio*, vol. 19, p. 100565, 2023.
- [2] M. Azeem, M. Shahid, I. Masin, and M. Petru, "Design and development of textile-based wearable sensors for real-time biomedical monitoring; a review," *The Journal of The Textile Institute*, vol. 116, no. 1, pp. 80-95, 2025.
- [3] M. R. Islam, S. Afroj, J. Yin, K. S. Novoselov, J. Chen, and N. Karim, "Advances in printed electronic textiles," *Advanced Science*, vol. 11, no. 6, p. 2304140, 2024.
- [4] C. Dang *et al.*, "Fibres—threads of intelligence—enable a new generation of wearable systems," *Chemical Society Reviews*, 2024.
- [5] X. Du, L. Yang, and N. Liu, "Recent progress on poly (3, 4-ethylenedioxythiophene): poly (styrenesulfonate) bioelectrodes," *Small Science*, vol. 3, no. 7, p. 2300008, 2023.
- [6] M. Atta and Q. Zhang, "Recent advances in 2D materials for smart textiles," *FlatChem*, vol. 42, p. 100562, 2023.
- [7] C. Zhang, Z. Xiao, R. Paddock, M. Cullinan, M. Tehrani, and Y. Liu, "Effects of Graphene Doping on the Electrical Conductivity of Copper," *Advanced Functional Materials*, vol. 34, no. 45, p. 2407569, 2024.
- [8] J. Wang *et al.*, "MoS<sub>2</sub> lubricate-toughened MXene/ANF composites for multifunctional electromagnetic interference shielding," *Nano-Micro Letters*, vol. 17, no. 1, p. 36, 2025.
- [9] K. S. Novoselov *et al.*, "Electric field effect in atomically thin carbon films," *science*, vol. 306, no. 5696, pp. 666-669, 2004.
- [10] S. Goenka, V. Sant, and S. Sant, "Graphene-based nanomaterials for drug delivery and tissue engineering," *Journal of Controlled Release*, vol. 173, pp. 75-88, 2014.
- [11] S. K. Tiwari, S. Sahoo, N. Wang, and A. Huczko, "Graphene research and their outputs: Status and prospect," *Journal of Science: Advanced Materials and Devices*, vol. 5, no. 1, pp. 10-29, 2020.
- [12] Q. Tang, Z. Zhou, and Z. Chen, "Innovation and discovery of graphene-like materials via density-functional theory computations," *Wiley Interdisciplinary Reviews: Computational Molecular Science*, vol. 5, no. 5, pp. 360-379, 2015.
- [13] 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.

- [14] A. Lee, M. Shekhirev, M. Anayee, and Y. Gogotsi, "Multi-year study of environmental stability of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene films," *Graphene and 2D materials*, vol. 9, no. 1, pp. 77-85, 2024.
- [15] O. Salim, K. Mahmoud, K. Pant, and R. Joshi, "Introduction to MXenes: synthesis and characteristics," *Materials Today Chemistry*, vol. 14, p. 100191, 2019.
- [16] 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.
- [17] H. Li *et al.*, "Effect of morphology and structure of MXene Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> on mechanical, thermal properties of PEEK nanocomposite," *Carbon*, vol. 228, p. 119436, 2024.
- [18] D. Zhang *et al.*, "Flexible room temperature gas sensor based on  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>/Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene composites for ppb-level H<sub>2</sub>S detection," *Sensors and Actuators B: Chemical*, vol. 421, p. 136543, 2024/12/15/ 2024.
- [19] J. Li, C. Guo, and C. M. Li, "Recent advances of two-dimensional (2 D) MXenes and phosphorene for high-performance rechargeable batteries," *ChemSusChem*, vol. 13, no. 6, pp. 1047-1070, 2020.
- [20] K. Li *et al.*, "3D MXene architectures for efficient energy storage and conversion," *Advanced Functional Materials*, vol. 30, no. 47, p. 2000842, 2020.
- [21] A. Levitt, J. Zhang, G. Dion, Y. Gogotsi, and J. M. Razal, "MXene-Based Fibers, Yarns, and Fabrics for Wearable Energy Storage Devices," *Advanced Functional Materials*, vol. 30, no. 47, p. 2000739, 2020.
- [22] A. Patra and C. S. Rout, "Architecturally robust MoWS<sub>2</sub> and Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene nanosheets hybrid for high-performance energy storage and conversion applications," *Energy Storage*, vol. 5, no. 3, p. e411, 2023.
- [23] H. T. A. Awan *et al.*, "MXene-polymer hybrid composites for advanced energy storage: Insights into supercapacitors and batteries," *Journal of Energy Storage*, vol. 95, p. 112449, 2024.
- [24] İ. K. Duygun, B. Küçükelyas, and A. Bedeloğlu, "Structurally integrated Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene/cotton fabric electrodes for supercapacitor applications," *Materials Research Bulletin*, vol. 180, p. 113042, 2024.
- [25] M. A. Nazir *et al.*, "Recent advances in MXene nanomaterials: Fundamentals to applications in environment sector," *EcoEnergy*, vol. 2, no. 4, pp. 505-548, 2024.

- [26] M. Tahir, "Introduction to Titanium Carbide (Ti<sub>3</sub>C<sub>2</sub>) MXenes for Energy and Environmental Applications," *Titanium Carbide MXenes: Synthesis, Characterization, Energy and Environmental Applications*, pp. 1-7, 2024.
- [27] U. Pengsomjit *et al.*, "Recent advances and analytical perspectives in MXene-based electrochemical miniaturized sensors for environmental analysis and monitoring," *Microchemical Journal*, p. 111433, 2024.
- [28] X. Zhang *et al.*, "A review on optoelectronic device applications of 2D transition metal carbides and nitrides," *Materials & Design*, vol. 200, p. 109452, 2021.
- [29] Z. Liu and H. N. Alshareef, "MXenes for optoelectronic devices," *Advanced electronic materials*, vol. 7, no. 9, p. 2100295, 2021.
- [30] B. U. Haq *et al.*, "V<sub>2</sub>XT<sub>2</sub> (X: C, N; T: O, F) MXenes; potential two-dimensional materials for spintronics, optoelectronics, and photovoltaic applications," *Materials Today Communications*, vol. 40, p. 109370, 2024.
- [31] R. Akhter and S. S. Maktedar, "MXenes: A comprehensive review of synthesis, properties, and progress in supercapacitor applications," *Journal of Materiomics*, vol. 9, no. 6, pp. 1196-1241, 2023.
- [32] M. Irfan, M. Ali, T. Khan, S. Anwer, K. Liao, and R. Umer, "MXene and graphene coated multifunctional fiber reinforced aerospace composites with sensing and EMI shielding abilities," *Composites Part A: Applied Science and Manufacturing*, vol. 165, p. 107351, 2023.
- [33] A. Parihar, N. K. Choudhary, P. Sharma, and R. Khan, "MXene-based aptasensor for the detection of aflatoxin in food and agricultural products," *Environmental Pollution*, vol. 316, p. 120695, 2023.
- [34] M. Shoaib *et al.*, "Emerging MXene-Based Aptasensors: A Paradigm Shift in Food Safety Detection," *Trends in Food Science & Technology*, p. 104635, 2024.
- [35] N. Tyagi, V. Bhardwaj, S. Moka, M. K. Singh, M. Khanuja, and G. Sharma, "An overview on synthesis of MXene and MXene based nanocomposites for supercapacitors," *Materials Today Communications*, p. 110223, 2024.
- [36] W. Cao *et al.*, "A review of how to improve Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene stability," *Chemical Engineering Journal*, p. 154097, 2024.
- [37] T. Jiang, Y. Wang, and G. Z. Chen, "Electrochemistry of titanium carbide MXenes in supercapacitor," *Small Methods*, vol. 7, no. 8, p. 2201724, 2023.

- [38] X. Gao *et al.*, "Synthesis of NiCo-LDH/MXene hybrids with abundant heterojunction surfaces as a lightweight electromagnetic wave absorber," *Chemical Engineering Journal*, vol. 419, p. 130019, 2021.
- [39] S. Ullah *et al.*, "MXene nanomaterials: synthesis, properties and applications in energy and environment sector," *Journal of Alloys and Compounds*, p. 175172, 2024.
- [40] M. Naguib *et al.*, "Two-dimensional nanocrystals produced by exfoliation of  $\text{Ti}_3\text{AlC}_2$ ," in *MXenes*: Jenny Stanford Publishing, 2023, pp. 15-29.
- [41] K. Khan *et al.*, "Recent Advances in Non-Ti MXenes: Synthesis, Properties, and Novel Applications," *Advanced Science*, vol. 11, no. 36, p. 2303998, 2024.
- [42] J. Jiang, R. Zhang, and W. Wu, "Wearable Sensors Based on Atomically Thin P-Type Semiconductors," *Advanced Materials Technologies*, vol. 8, no. 18, p. 2300517, 2023.
- [43] M. Rdest and D. Janas, "Carbon nanotube wearable sensors for health diagnostics," *Sensors*, vol. 21, no. 17, p. 5847, 2021.
- [44] M. R. Repon *et al.*, "Progress in MXene integrated wearable textile devices for thermotherapy," *Materials Today Communications*, vol. 37, p. 107251, 2023.
- [45] J. Li, W. Zhang, L. Yang, and S. Yin, "Conductive fabrics based on carbon nanotube/ $\text{Ti}_3\text{C}_2\text{T}_x$  MXene/polyaniline/liquid metal quaternary composites with improved performance of EMI shielding and joule heating," *Composites Communications*, vol. 38, p. 101476, 2023.
- [46] S. Ding *et al.*, "Integrating  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene Nanosheets with Thermoplastic Polyurethane Nanofibers as Wearable Humidity Sensors for Noninvasive Sleep Monitoring and Noncontact Sensing," *ACS Applied Nano Materials*, vol. 6, no. 13, pp. 11810-11821, 2023.
- [47] B. Abdi, A. Tarhini, H. Baniasadi, and A. R. Tehrani-Bagha, "Developing Graphene-based Conductive Textiles Using Different Coating Methods," *Advanced Materials Technologies*, vol. 9, no. 4, p. 2301492, 2024.
- [48] Y. Gogotsi and Q. Huang, "MXenes: two-dimensional building blocks for future materials and devices," vol. 15, ed: ACS Publications, 2021, pp. 5775-5780.
- [49] A. A. Smith, R. Li, L. Xu, and Z. T. H. Tse, "A Narrative Review of In-Textile Sensors in Human Health Applications," *Advanced Materials Technologies*, vol. 9, no. 16, p. 2302141, 2024.
- [50] R. Shekhar, N. A. Choudhry, S. Islam, A. Ahnood, E. Pirogova, and O. Troynikov, "A novel elastic conductive yarn for smart textile applications," *Advanced Engineering Materials*, vol. 25, no. 22, p. 2300572, 2023.

- [51] W. Shafik, "Smart biomedical devices for smart healthcare," in *Machine Learning Models and Architectures for Biomedical Signal Processing*: Elsevier, 2025, pp. 421-448.
- [52] S. Mehrotra, P. Rai, A. Saxena, S. Priya, and S. K. Sharma, "Advancements in enzyme-based wearable sensors for health monitoring," *Microchemical Journal*, vol. 200, p. 110250, 2024.
- [53] K. Keum, J. Eom, J. H. Lee, J. S. Heo, S. K. Park, and Y.-H. Kim, "Fully-integrated wearable pressure sensor array enabled by highly sensitive textile-based capacitive ionotronic devices," *Nano Energy*, vol. 79, p. 105479, 2021.
- [54] H. Luo and B. Gao, "Development of smart wearable sensors for life healthcare," *Engineered Regeneration*, vol. 2, pp. 163-170, 2021.
- [55] T. Blachowicz, G. Ehrmann, and A. Ehrmann, "Textile-Based Sensors for Biosignal Detection and Monitoring," *Sensors*, vol. 21, no. 18, p. 6042, 2021.
- [56] N. M. Ghahjaverstan *et al.*, "Textile-based wearable to monitor heart activity in paediatric population: a pilot study," *CJC Pediatric and Congenital Heart Disease*, vol. 2, no. 4, pp. 187-195, 2023.
- [57] B. Nie *et al.*, "Textile-based wireless pressure sensor array for human-interactive sensing," *Advanced functional materials*, vol. 29, no. 22, p. 1808786, 2019.
- [58] M. M. Safaee, M. Gravely, and D. Roxbury, "A wearable optical microfibrous biomaterial with encapsulated nanosensors enables wireless monitoring of oxidative stress," *Advanced functional materials*, vol. 31, no. 13, p. 2006254, 2021.
- [59] W. Yu *et al.*, "A sensor platform based on SERS detection/janus textile for sweat glucose and lactate analysis toward portable monitoring of wellness status," *Biosensors and Bioelectronics*, vol. 263, p. 116612, 2024.
- [60] Q. Liu *et al.*, "All textile-based robust pressure sensors for smart garments," *Chemical Engineering Journal*, vol. 454, p. 140302, 2023.
- [61] G. Cay *et al.*, "An e-textile respiration sensing system for NICU monitoring: Design and validation," *Journal of Signal Processing Systems*, pp. 1-15, 2022.
- [62] J. Wekalao, A. Baz, and S. K. Patel, "Design and analysis of high-sensitivity hormone sensor with KNN behavior prediction for healthcare and biomedical applications," *Measurement*, vol. 242, p. 116172, 2025.
- [63] K. Sankar, U. Kuzmanović, S. E. Schaus, J. E. Galagan, and M. W. Grinstaff, "Strategy, design, and fabrication of electrochemical biosensors: a tutorial," *ACS sensors*, vol. 9, no. 5, pp. 2254-2274, 2024.

- [64] R. B. Satpathy, R. G. Paneesh, and S. Kannan, "Optimal design of novel plasmonic antenna based label free biomedical sensor using Firefly algorithm," *Optik*, vol. 320, p. 172139, 2025.
- [65] N. A. Mohammed, O. E. Khedr, E.-S. M. El-Rabaie, and A. A. Khalaf, "Tuberculosis biomedical sensor based on on-chip nanocavity 2D photonic crystal with high sensitivity and quality factor," *Measurement*, vol. 222, p. 113595, 2023.
- [66] N. A. Mohammed, O. E. Khedr, E.-S. M. El-Rabaie, and A. A. Khalaf, "Brain tumors biomedical sensor with high-quality factor and ultra-compact size based on nanocavity 2D photonic crystal," *Alexandria Engineering Journal*, vol. 64, pp. 527-540, 2023.
- [67] H. T. Zhu *et al.*, "Self-assembled wavy optical microfiber for stretchable wearable sensor," *Advanced Optical Materials*, vol. 9, no. 11, p. 2002206, 2021.
- [68] M. Takaya *et al.*, "Transformable electrocardiograph using robust liquid–solid heteroconnector," *Acs Sensors*, vol. 6, no. 1, pp. 212-219, 2021.
- [69] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiological measurement*, vol. 28, no. 3, p. R1, 2007.
- [70] T. Aoyagi, "Pulse oximetry: its invention, theory, and future," *Journal of anesthesia*, vol. 17, pp. 259-266, 2003.
- [71] O. Anton, R. Fernandez, E. Rendon-Morales, R. Aviles-Espinosa, H. Jordan, and H. Rabe, "Heart rate monitoring in newborn babies: a systematic review," *Neonatology*, vol. 116, no. 3, pp. 199-210, 2019.
- [72] K. Torp, P. Modi, and L. Simon, "Pulse Oximetry.[Updated 2022 Aug 10]," *StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing*, 2023.
- [73] T. Greenhalgh, M. Knight, M. Inada-Kim, N. J. Fulop, J. Leach, and C. Vindrola-Padros, "Remote management of covid-19 using home pulse oximetry and virtual ward support," *bmj*, vol. 372, 2021.
- [74] P. H. Charlton, P. A. Kyriacou, J. Mant, V. Marozas, P. Chowienczyk, and J. Alastruey, "Wearable Photoplethysmography for Cardiovascular Monitoring," *Proceedings of the IEEE*, vol. 110, no. 3, pp. 355-381, 2022.
- [75] S. Brookman *et al.*, "Pulse oximetry in patients with pigmented skin: What I should know," *Paediatric Respiratory Reviews*, 2024.
- [76] M. W. Sjoding, R. P. Dickson, T. J. Iwashyna, S. E. Gay, and T. S. Valley, "Racial bias in pulse oximetry measurement," *New England Journal of Medicine*, vol. 383, no. 25, pp. 2477-2478, 2020.

- [77] M. S. Lipnick, O. Ehie, E. N. Igaga, and P. Bicker, "Pulse Oximetry and Skin Pigmentation—New Guidance From the FDA," *JAMA*, vol. 333, no. 16, pp. 1393-1395, 2025.
- [78] S. K. N. Swamy, C. He, B. R. Hayes-Gill, D. J. Clark, S. Green, and S. P. Morgan, "Pulse oximeter bench tests under different simulated skin tones," *Medical & Biological Engineering & Computing*, pp. 1-12, 2024.
- [79] D. Han *et al.*, "Pulse Oximetry Using Organic Optoelectronics under Ambient Light," *Advanced Materials Technologies*, vol. 5, no. 5, p. 1901122, 2020.
- [80] C. Zavaleta *et al.*, "Pressure Pro: A Wireless Medical Prototype for Integrated Blood Pressure and Pulse Oximetry Monitoring," in *Congreso Nacional de Ingeniería Biomédica*, 2024, pp. 267-277: Springer.
- [81] E. B. Bahadır and M. K. Sezginürk, "Electrochemical biosensors for hormone analyses," *Biosensors and Bioelectronics*, vol. 68, pp. 62-71, 2015/06/15/ 2015.
- [82] M. T. Ghoneim *et al.*, "Recent Progress in Electrochemical pH-Sensing Materials and Configurations for Biomedical Applications," *Chemical Reviews*, vol. 119, no. 8, pp. 5248-5297, 2019/04/24 2019.
- [83] Y. Li, S. Song, J. Song, R. Gong, and G. Abbas, "Electrochemical pH Sensor Incorporated Wearables for State-of-the-Art Wound Care," *ACS Sensors*, vol. 10, no. 3, pp. 1690-1708, 2025/03/28 2025.
- [84] R. Das, S. Nag, and P. Banerjee, "Electrochemical Nanosensors for Sensitization of Sweat Metabolites: From Concept Mapping to Personalized Health Monitoring," *Molecules*, vol. 28, no. 3, p. 1259, 2023.
- [85] Y. Hua *et al.*, "A Highly Stable Electrochemical Sensor Based on a Metal–Organic Framework/Reduced Graphene Oxide Composite for Monitoring the Ammonium in Sweat," *Biosensors*, vol. 14, no. 12, p. 617, 2024.
- [86] K. A. Nyni, L. K. Vincent, L. Varghese, V. L. Liya, A. N. Johny, and C. V. Yesudas, "Wireless health monitoring system for ECG, EMG and EEG detecting," in *2017 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)*, 2017, pp. 1-5.
- [87] T. Lu, S. Ji, W. Jin, Q. Yang, Q. Luo, and T.-L. Ren, "Biocompatible and long-term monitoring strategies of wearable, ingestible and implantable biosensors: reform the next generation healthcare," *Sensors*, vol. 23, no. 6, p. 2991, 2023.

- [88] R. Omar *et al.*, "Biodegradable, Biocompatible, and Implantable Multifunctional Sensing Platform for Cardiac Monitoring," *ACS Sensors*, vol. 9, no. 1, pp. 126-138, 2024/01/26 2024.
- [89] R. Papani, Y. Li, and S. Wang, "Soft mechanical sensors for wearable and implantable applications," *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, vol. 16, no. 3, p. e1961, 2024.
- [90] S. Wang *et al.*, "Self-Adhesive, Stretchable, Biocompatible, and Conductive Nonvolatile Eutectogels as Wearable Conformal Strain and Pressure Sensors and Biopotential Electrodes for Precise Health Monitoring," *ACS Applied Materials & Interfaces*, vol. 13, no. 17, pp. 20735-20745, 2021/05/05 2021.
- [91] F. He *et al.*, "Stretchable, Biocompatible, and Multifunctional Silk Fibroin-Based Hydrogels toward Wearable Strain/Pressure Sensors and Triboelectric Nanogenerators," *ACS Applied Materials & Interfaces*, vol. 12, no. 5, pp. 6442-6450, 2020/02/05 2020.
- [92] M. Uddin and S. Syed-Abdul, "Data Analytics and Applications of the Wearable Sensors in Healthcare: An Overview," (in eng), *Sensors (Basel)*, vol. 20, no. 5, Mar 3 2020.
- [93] E. Refaee *et al.*, "Secure and Scalable Healthcare Data Transmission in IoT Based on Optimized Routing Protocols for Mobile Computing Applications," *Wireless Communications and Mobile Computing*, vol. 2022, no. 1, p. 5665408, 2022.
- [94] S. K. Sahu and K. Mazumdar, "Exploring security threats and solutions Techniques for Internet of Things (IoT): from vulnerabilities to vigilance," (in eng), *Front Artif Intell*, vol. 7, p. 1397480, 2024.
- [95] T. Sasi, A. H. Lashkari, R. Lu, P. Xiong, and S. Iqbal, "A comprehensive survey on IoT attacks: Taxonomy, detection mechanisms and challenges," *Journal of Information and Intelligence*, vol. 2, no. 6, pp. 455-513, 2024/11/01/ 2024.
- [96] S. Pandey, M. Chaudhary, and Z. Tóth, "An investigation on real-time insights: enhancing process control with IoT-enabled sensor networks," *Discover Internet of Things*, vol. 5, no. 1, p. 29, 2025/03/20 2025.
- [97] I. Coston, E. Plotnizky, and M. Nojournian, "Comprehensive Study of IoT Vulnerabilities and Countermeasures," *Applied Sciences*, vol. 15, no. 6, p. 3036, 2025.
- [98] L. Verger, C. Xu, V. Natu, H.-M. Cheng, W. Ren, and M. W. Barsoum, "Overview of the synthesis of MXenes and other ultrathin 2D transition metal carbides and nitrides,"

- Current Opinion in Solid State and Materials Science*, vol. 23, no. 3, pp. 149-163, 2019.
- [99] J. Huang, Z. Li, Y. Mao, and Z. Li, "Progress and biomedical applications of MXenes," *Nano Select*, vol. 2, no. 8, pp. 1480-1508, 2021.
- [100] U. U. Rahman *et al.*, "MXenes as Emerging Materials: Synthesis, Properties, and Applications," *Molecules*, vol. 27, no. 15, p. 4909, 2022.
- [101] S. Jayakumar, P. C. Santhosh, S. Ramakrishna, and A. V. Radhamani, "2D (Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>) MXene: A comprehensive review of advancements in synthesis protocols, applications in supercapacitors, sustainability targets and future prospects," *Journal of Energy Storage*, vol. 97, p. 112741, 2024/09/01/ 2024.
- [102] M. A. Ahouei, T. H. Syed, V. Bishop, S. Halacoglu, H. Wang, and W. Wei, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene framework materials: Preparation, properties and applications in energy and environment," *Catalysis Today*, vol. 409, pp. 162-172, 2023/02/01/ 2023.
- [103] T. S. Mathis *et al.*, "Modified MAX Phase Synthesis for Environmentally Stable and Highly Conductive Ti<sub>3</sub>C<sub>2</sub> MXene," *ACS Nano*, vol. 15, no. 4, pp. 6420-6429, 2021/04/27 2021.
- [104] S. S. Siwal, H. Kaur, G. Chauhan, and V. K. Thakur, "MXene-Based Nanomaterials for Biomedical Applications: Healthier Substitute Materials for the Future," *Advanced NanoBiomed Research*, vol. 3, no. 1, p. 2200123, 2023.
- [105] A. Thakur *et al.*, "Step-by-Step Guide for Synthesis and Delamination of Ti<sub>3</sub>C<sub>2</sub>T MXene," *Small Methods*, vol. 7, no. 8, p. 2300030, 2023.
- [106] Y. Liu *et al.*, "Efficient mechanical exfoliation of MXene nanosheets," *Chemical Engineering Journal*, vol. 468, p. 143439, 2023.
- [107] B. Chaw pattnayak, N. Panda, and S. Mohapatra, "Facile synthesis of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene nanosheets using aryl diazonium tetrafluoroborate for multiple applications," *Carbon*, vol. 230, p. 119609, 2024/11/01/ 2024.
- [108] A. Pazniak *et al.*, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene characterization produced from SHS-ground Ti<sub>3</sub>AlC<sub>2</sub>," *Materials & Design*, vol. 183, p. 108143, 2019/12/05/ 2019.
- [109] Nidhi *et al.*, "An overview on synthesis of MXene and MXene based nanocomposites for supercapacitors," *Materials Today Communications*, vol. 41, p. 110223, 2024/12/01/ 2024.
- [110] M. Alhabeb *et al.*, "Guidelines for Synthesis and Processing of Two-Dimensional Titanium Carbide (Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene)," *Chemistry of Materials*, vol. 29, no. 18, pp. 7633-7644, 2017/09/26 2017.

- [111] B. Anasori, Maria R. Lukatskaya, and Yury Gogotsi, "2D metal carbides and nitrides (MXenes) for energy storage," in *MXenes* 1st ed.: Jenny Stanford Publishing, 2023, pp. 677-722.
- [112] A. M. Patil *et al.*, "Recent progress of MXene synthesis, properties, microelectrode fabrication techniques for microsupercapacitors and microbatteries energy storage devices and integration: A comprehensive review," *Coordination Chemistry Reviews*, vol. 517, p. 216020, 2024/10/15/ 2024.
- [113] M. Askkar Deen, H. Kumar Rajendran, R. Chandrasekar, D. Ghosh, and S. Narayanasamy, "The Rise of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene synthesis strategies over the decades: A review," *FlatChem*, vol. 47, p. 100734, 2024/09/01/ 2024.
- [114] R. Khaledialidusti, M. Khazaei, S. Khazaei, and K. Ohno, "High-throughput computational discovery of ternary-layered MAX phases and prediction of their exfoliation for formation of 2D MXenes," *Nanoscale*, 10.1039/D0NR08791B vol. 13, no. 15, pp. 7294-7307, 2021.
- [115] M. Ghidui, 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, no. 7529, pp. 78-81, 2014/12/01 2014.
- [116] A. Sarycheva, Yury Gogotsi., "Raman Spectroscopy Analysis of the Structure and Surface Chemistry of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene," in *MXenes* 1st ed.: Jenny Stanford Publishing, 2023, pp. 333-355.
- [117] K. Huang, Z. Li, J. Lin, G. Han, and P. Huang, "Two-dimensional transition metal carbides and nitrides (MXenes) for biomedical applications," *Chemical Society Reviews*, 10.1039/C7CS00838D vol. 47, no. 14, pp. 5109-5124, 2018.
- [118] A. Zamhuri, G. P. Lim, N. L. Ma, K. S. Tee, and C. F. Soon, "MXene in the lens of biomedical engineering: synthesis, applications and future outlook," *BioMedical Engineering OnLine*, vol. 20, no. 1, p. 33, 2021/04/01 2021.
- [119] L. Gao *et al.*, "MXene/polymer membranes: synthesis, properties, and emerging applications," *Chemistry of Materials*, vol. 32, no. 5, pp. 1703-1747, 2020.
- [120] V. A. Tran, N. T. Tran, V. D. Doan, T.-Q. Nguyen, H. H. Pham Thi, and G. N. L. Vo, "Application Prospects of MXenes Materials Modifications for Sensors," *Micromachines*, vol. 14, no. 2, p. 247, 2023.
- [121] R. Verma, A. Sharma, V. Dutta, A. Chauhan, D. Pathak, and S. Ghotekar, "Recent trends in synthesis of 2D MXene-based materials for sustainable environmental applications," *Emergent Materials*, vol. 7, no. 1, pp. 35-62, 2024/02/01 2024.

- [122] G. Zhang *et al.*, "Bottom-up synthesis of 2D heterostructures enables effective polysulfides inhibition and conversion," *Nano Research*, vol. 16, no. 6, pp. 8488-8496, 2023/06/01 2023.
- [123] H. T. A. Awan, L. Kumar, W. P. Wong, R. Walvekar, and M. Khalid, "Recent progress and challenges in MXene-based phase change material for solar and thermal energy applications," *Energies*, vol. 16, no. 4, p. 1977, 2023.
- [124] Y. Gogotsi, "Transition metal carbides go 2D," *Nature materials*, vol. 14, no. 11, pp. 1079-1080, 2015.
- [125] C. Xu, L. Chen, Z. Liu, H.-M. Cheng, and W. Ren, "Bottom-Up Synthesis of 2D Transition Metal Carbides and Nitrides," in *2D Metal Carbides and Nitrides (MXenes): Structure, Properties and Applications*, B. Anasori and Y. Gogotsi, Eds. Cham: Springer International Publishing, 2019, pp. 89-109.
- [126] R. Zhang, Y. Sun, F. Jiao, L. Li, D. Geng, and W. Hu, "MXene-MoS<sub>2</sub> nanocomposites via chemical vapor deposition with enhanced electrocatalytic activity for hydrogen evolution," *Nano Research*, vol. 16, no. 7, pp. 8937-8944, 2023/07/01 2023.
- [127] D. Wang *et al.*, "Direct synthesis and chemical vapor deposition of 2D carbide and nitride MXenes," *Science*, vol. 379, no. 6638, pp. 1242-1247, 2023.
- [128] S. Joshi, Q. Wang, A. Puntambekar, and V. Chakrapani, "Facile Synthesis of Large Area Two-Dimensional Layers of Transition-Metal Nitride and Their Use as Insertion Electrodes," *ACS Energy Letters*, vol. 2, no. 6, pp. 1257-1262, 2017/06/09 2017.
- [129] A. Lipatov *et al.*, "High electrical conductivity and breakdown current density of individual monolayer Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene flakes," *Matter*, vol. 4, no. 4, pp. 1413-1427, 2021.
- [130] P. Eklund, M. Beckers, U. Jansson, H. Högberg, and L. Hultman, "The Mn<sub>1</sub>AX<sub>n</sub> phases: Materials science and thin-film processing," *Thin Solid Films*, vol. 518, no. 8, pp. 1851-1878, 2010/02/01/ 2010.
- [131] D. N. Ampong *et al.*, "MXene: fundamentals to applications in electrochemical energy storage," *Discover Nano*, vol. 18, no. 1, p. 3, 2023/02/03 2023.
- [132] Y. Wang *et al.*, "Ultrasmall Mo<sub>2</sub>C Nanoparticle-Decorated Carbon Polyhedrons for Enhanced Microwave Absorption," *ACS Applied Nano Materials*, vol. 1, no. 9, pp. 5366-5376, 2018/09/28 2018.
- [133] J. Chen *et al.*, "Molten Salt-Shielded Synthesis (MS<sub>3</sub>) of MXenes in Air," *ENERGY & ENVIRONMENTAL MATERIALS*, vol. 6, no. 2, p. e12328, 2023.

- [134] H. Cheng, L.-X. Ding, G.-F. Chen, L. Zhang, J. Xue, and H. Wang, "Molybdenum Carbide Nanodots Enable Efficient Electrocatalytic Nitrogen Fixation under Ambient Conditions," *Advanced Materials*, vol. 30, no. 46, p. 1803694, 2018.
- [135] L. Chen, X. Shi, N. Yu, X. Zhang, X. Du, and J. Lin, "Measurement and Analysis of Thermal Conductivity of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene Films," *Materials*, vol. 11, no. 9, p. 1701, 2018.
- [136] X. Shi *et al.*, "Experimental research on thermal transport properties of palladium-based amorphous alloys," *Journal of Non-Crystalline Solids*, vol. 458, pp. 157-161, 2017/02/15/ 2017.
- [137] R. Taherian, "Experimental and analytical model for the electrical conductivity of polymer-based nanocomposites," *Composites Science and Technology*, vol. 123, pp. 17-31, 2016/02/08/ 2016.
- [138] H. Li and Z. Du, "MXene fiber-based wearable textiles in sensing and energy storage applications," *Fibers and Polymers*, vol. 24, no. 4, pp. 1167-1182, 2023.
- [139] H. Liu, C. Duan, C. Yang, W. Shen, F. Wang, and Z. Zhu, "A novel nitrite biosensor based on the direct electrochemistry of hemoglobin immobilized on MXene-Ti<sub>3</sub>C<sub>2</sub>," *Sensors and Actuators B: Chemical*, vol. 218, pp. 60-66, 2015.
- [140] S. P. Sreenilayam, I. Ul Ahad, V. Nicolosi, and D. Brabazon, "MXene materials based printed flexible devices for healthcare, biomedical and energy storage applications," *Materials Today*, vol. 43, pp. 99-131, 2021/03/01/ 2021.
- [141] J. S. Meena, S. B. Choi, S.-B. Jung, and J.-W. Kim, "Recent progress of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>-based MXenes for fabrication of multifunctional smart textiles," *Applied Materials Today*, vol. 29, p. 101612, 2022.
- [142] S. Seyedin *et al.*, "MXene composite and coaxial fibers with high stretchability and conductivity for wearable strain sensing textiles," *Advanced Functional Materials*, vol. 30, no. 12, p. 1910504, 2020.
- [143] R. M. Ronchi, J. T. Arantes, and S. F. Santos, "Synthesis, structure, properties and applications of MXenes: Current status and perspectives," *Ceramics International*, vol. 45, no. 15, pp. 18167-18188, 2019.
- [144] W. X. R. Leong, A. M. Al-Dhahebi, M. R. Ahmad, and M. S. M. Saheed, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-polymeric strain sensor with huge gauge factor for body movement detection," *Micromachines*, vol. 13, no. 8, p. 1302, 2022.

- [145] N. Duan *et al.*, "Mechanically robust Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene/Carbon fiber fabric/Thermoplastic polyurethane composite for efficient electromagnetic interference shielding applications," *Materials & Design*, vol. 214, p. 110382, 2022.
- [146] J. Peng *et al.*, "Superhydrophobic MXene-based fabric with electromagnetic interference shielding and thermal management ability for flexible sensors," *Advanced Fiber Materials*, vol. 5, no. 6, pp. 2099-2113, 2023.
- [147] S. Duan *et al.*, "Highly sensitive and mechanically stable MXene textile sensors for adaptive smart data glove embedded with near-sensor edge intelligence," *Advanced Fiber Materials*, vol. 6, no. 5, pp. 1541-1553, 2024.
- [148] G. He *et al.*, "High-performance and long-term stability of MXene/PEDOT: PSS-decorated cotton yarn for wearable electronics applications," *Advanced Fiber Materials*, vol. 6, no. 2, pp. 367-386, 2024.
- [149] R. Liu *et al.*, "MXene-coated air-permeable pressure-sensing fabric for smart wear," *ACS Applied Materials & Interfaces*, vol. 12, no. 41, pp. 46446-46454, 2020.
- [150] X. Zhao *et al.*, "Smart Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene fabric with fast humidity response and joule heating for healthcare and medical therapy applications," *ACS nano*, vol. 14, no. 7, pp. 8793-8805, 2020.
- [151] Q. Yu *et al.*, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>@ nonwoven fabric composite: promising MXene-coated fabric for wearable piezoresistive pressure sensors," *ACS Applied Materials & Interfaces*, vol. 14, no. 7, pp. 9632-9643, 2022.
- [152] İ. K. Duygun and A. Bedeloğlu, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene/reduced graphene oxide/cellulose nanocrystal-coated cotton fabric electrodes for supercapacitor applications," *Journal of Materials Science*, vol. 59, no. 21, pp. 9455-9471, 2024.
- [153] M. Shi *et al.*, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-Decorated Nanoporous Polyethylene Textile for Passive and Active Personal Precision Heating," *ACS Nano*, vol. 15, no. 7, pp. 11396-11405, 2021/07/27 2021.
- [154] A. Ahmed, M. M. Hossain, B. Adak, and S. Mukhopadhyay, "Recent advances in 2D MXene integrated smart-textile interfaces for multifunctional applications," *Chemistry of Materials*, vol. 32, no. 24, pp. 10296-10320, 2020.
- [155] W. Wang, Y. Zhu, P. Ghosh, and Q. Li, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene Decorated Textiles with Low Thermal Emissivity," in *Journal of Physics: Conference Series*, 2022, vol. 2242, no. 1, p. 012008: IOP Publishing.

- [156] S. Yong *et al.*, "Ti<sub>3</sub>C<sub>2</sub> MXene as Additive for Low-Cost Textile Supercapacitors with Enhanced Electrical Performance," *Advanced Materials Technologies*, vol. 9, no. 2, p. 2301266, 2024.
- [157] B. Yan *et al.*, "Antioxidative MXene@ GA-decorated textile assisted by metal ion for efficient electromagnetic interference shielding, dual-driven heating, and infrared thermal camouflage," *Advanced Fiber Materials*, vol. 5, no. 6, pp. 2080-2098, 2023.
- [158] W. Feng, L. Zou, C. Lan, S. E, and X. Pu, "Core-sheath CNT@ MXene fibers toward absorption-dominated electromagnetic interference shielding fabrics," *Advanced Fiber Materials*, vol. 6, no. 5, pp. 1657-1668, 2024.
- [159] P. Zhang *et al.*, "Integrated Textile Supercapacitors Enhanced with Energy-Absorbing Spacer Fabrics and Ti<sub>3</sub>C<sub>2</sub>T MXene," *Advanced Functional Materials*, vol. 34, no. 40, p. 2403601, 2024.
- [160] A. M. Grancarić *et al.*, "Conductive polymers for smart textile applications," *Journal of Industrial Textiles*, vol. 48, no. 3, pp. 612-642, 2018.
- [161] M. Goyal, K. Singh, and N. Bhatnagar, "Conductive polymers: A multipurpose material for protecting coating," *Progress in Organic Coatings*, vol. 187, p. 108083, 2024.
- [162] K. Namsheer and C. S. Rout, "Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications," *RSC advances*, vol. 11, no. 10, pp. 5659-5697, 2021.
- [163] V. K. Chauhan, R. Dubey, R. Pandey, P. Thennarasu, and S. K. Dubey, "MXene on Textile Substrates: A Review," *Advanced Engineering Materials*, vol. 26, no. 7, p. 2301962, 2024.
- [164] A. Di *et al.*, "MXene-based solvent-responsive actuators with a polymer-intercalated gradient structure," *Chemical Science*, vol. 16, no. 5, pp. 2191-2201, 2025.
- [165] M. Hussain *et al.*, "Recent advances and future prospects of Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-based electrochemical sensors: A review," *Microchemical Journal*, p. 111495, 2024.
- [166] Q. Zhang *et al.*, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>-MXene/PET textile-based flexible pressure sensor for wearable pulse monitoring," *Journal of Materials Chemistry C*, 10.1039/D3TC02970K vol. 11, no. 44, pp. 15638-15648, 2023.
- [167] S. Zou, D. Li, C. He, X. Wang, D. Cheng, and G. Cai, "Scalable fabrication of an mxene/cotton/spandex yarn for intelligent wearable applications," *ACS Applied Materials & Interfaces*, vol. 15, no. 8, pp. 10994-11003, 2023.

- [168] C. Ma, Q. Yuan, H. Du, M.-G. Ma, C. Si, and P. Wan, "Multiresponsive MXene ( $\text{Ti}_3\text{C}_2\text{T}_x$ )-Decorated Textiles for Wearable Thermal Management and Human Motion Monitoring," 2020.
- [169] M. Yadav, M. Kumar, and A. Sharma, "Review of  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene Nanosheets and their Applications," *ACS Applied Nano Materials*, vol. 7, no. 9, pp. 9847-9867, 2024.
- [170] M. Tariq *et al.*, "MXenes and  $\text{CO}_2$ : A pioneering journey towards sustainable electrochemical reduction," *International Journal of Hydrogen Energy*, vol. 96, pp. 1281-1298, 2024.
- [171] X. Wang, M. Li, S. Yang, X. Bai, and J. Shan, "Self-assembled  $\text{Ti}_3\text{C}_2\text{TX}$  MXene/graphene composite for the electrochemical reduction and detection of p-nitrophenol," *Microchemical Journal*, vol. 179, p. 107473, 2022.
- [172] H. Wei *et al.*, " $\text{Ti}_3\text{C}_2\text{Tx}$  MXene/polyaniline (PANI) sandwich intercalation structure composites constructed for microwave absorption," *Composites Science and Technology*, vol. 169, pp. 52-59, 2019.
- [173] S. Bai, X. Guo, X. Zhang, X. Zhao, and H. Yang, " $\text{Ti}_3\text{C}_2\text{Tx}$  MXene-AgNW composite flexible transparent conductive films for EMI shielding," *Composites Part A: Applied Science and Manufacturing*, vol. 149, p. 106545, 2021.
- [174] Y. Cai *et al.*, " $\text{Ti}_3\text{C}_2\text{Tx}$  MXene/carbon composites for advanced supercapacitors: Synthesis, progress, and perspectives," *Carbon Energy*, vol. 6, no. 2, p. e501, 2024.
- [175] X. Zheng *et al.*, "Multifunctional RGO/ $\text{Ti}_3\text{C}_2\text{Tx}$  MXene fabrics for electrochemical energy storage, electromagnetic interference shielding, electrothermal and human motion detection," *Materials & Design*, vol. 200, p. 109442, 2021.
- [176] L.-X. Liu *et al.*, "Tough and electrically conductive  $\text{Ti}_3\text{C}_2\text{Tx}$  MXene-based core-shell fibers for high-performance electromagnetic interference shielding and heating application," *Chemical Engineering Journal*, vol. 430, p. 133074, 2022.
- [177] Y. Pei *et al.*, " $\text{Ti}_3\text{C}_2\text{TX}$  MXene for sensing applications: recent progress, design principles, and future perspectives," *ACS nano*, vol. 15, no. 3, pp. 3996-4017, 2021.
- [178] I. Navitski, A. Ramanaviciute, S. Ramanavicius, M. Pogorielov, and A. Ramanavicius, "MXene-based chemo-sensors and other sensing devices," *Nanomaterials*, vol. 14, no. 5, p. 447, 2024.
- [179] M. Mathew and C. S. Rout, "Electrochemical biosensors based on  $\text{Ti}_3\text{C}_2\text{Tx}$  MXene: future perspectives for on-site analysis," *Current Opinion in Electrochemistry*, vol. 30, p. 100782, 2021.

- [180] Q. T. H. Ta, D. Thakur, and J.-S. Noh, "Design of functional Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene for gas sensors and energy harvesting: A review," *Chemosensors*, vol. 11, no. 9, p. 477, 2023.
- [181] Y. Chen *et al.*, "Refractive index sensors based on Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene fibers," *ACS Applied Nano Materials*, vol. 3, no. 1, pp. 303-311, 2020.
- [182] W. Waheed, S. Anwer, M. U. Khan, M. Sajjad, and A. Alazzam, "2D Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub>-MXene nanosheets and graphene oxide based highly sensitive humidity sensor for wearable and flexible electronics," *Chemical Engineering Journal*, vol. 480, p. 147981, 2024.
- [183] F.-L. Gao *et al.*, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-based multifunctional tactile sensors for precisely detecting and distinguishing temperature and pressure stimuli," *ACS nano*, vol. 17, no. 16, pp. 16036-16047, 2023.
- [184] S. H. Hosseini-Shokouh *et al.*, "Highly selective H<sub>2</sub>S gas sensor based on Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene–organic composites," *ACS Applied Materials & Interfaces*, vol. 15, no. 5, pp. 7063-7073, 2023.
- [185] Y. Lu *et al.*, "Flexible impedance sensor based on Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene and graphitic carbon nitride nanohybrid for humidity-sensing application with ultrahigh response," *Rare Metals*, vol. 42, no. 7, pp. 2204-2213, 2023.
- [186] L. Yao, X. Tian, X. Cui, R. Zhao, X. Xiao, and Y. Wang, "Partially oxidized Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-sensitive material-based ammonia gas sensor with high-sensing performances for room temperature application," *Journal of Materials Science: Materials in Electronics*, vol. 32, pp. 27837-27848, 2021.
- [187] H. Xing *et al.*, "MXene/MWCNT electronic fabric with enhanced mechanical robustness on humidity sensing for real-time respiration monitoring," *Sensors and Actuators B: Chemical*, vol. 361, p. 131704, 2022.
- [188] J. Luo *et al.*, "Superhydrophobic and breathable smart MXene-based textile for multifunctional wearable sensing electronics," *Chemical Engineering Journal*, vol. 406, p. 126898, 2021.
- [189] M. Chao *et al.*, "Breathable Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene/Protein nanocomposites for ultrasensitive medical pressure sensor with degradability in solvents," *ACS nano*, vol. 15, no. 6, pp. 9746-9758, 2021.
- [190] S. J. Kim *et al.*, "Metallic Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene gas sensors with ultrahigh signal-to-noise ratio," *ACS nano*, vol. 12, no. 2, pp. 986-993, 2018.

- [191] K. Khorsand Kazemi *et al.*, "Low-profile planar antenna sensor based on Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene membrane for VOC and humidity monitoring," *Advanced Materials Interfaces*, vol. 9, no. 13, p. 2102411, 2022.
- [192] X. Li *et al.*, "All-MXene-printed RF resonators as wireless plant wearable sensors for in situ ethylene detection," *Small*, vol. 19, no. 24, p. 2207889, 2023.
- [193] T. Yuan, R. Yin, C. Li, Z. Fan, and L. Pan, "Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene-based all-resistive dual-mode sensor with near-zero temperature coefficient of resistance for crosstalk-free pressure and temperature detections," *Chemical Engineering Journal*, vol. 487, p. 150396, 2024.
- [194] S. Uzun *et al.*, "Knittable and washable multifunctional MXene-coated cellulose yarns," *Advanced Functional Materials*, vol. 29, no. 45, p. 1905015, 2019.



**George Kwame Fobiri** is a PhD student (pursuing a PhD in Textile Design Technology) at Kwame Nkrumah University of Science and Technology (KNUST) and an Assistant Lecturer at the Department of Fashion Design and Textiles Studies at Kumasi Technical University, Ghana. He holds a bachelor's degree in Industrial Art (Textiles) and a master of Fine Arts (MFA) in Textile Design from the Department of Industrial Art, KNUST. His research interests cover textile design, fashion design, E-textiles, wearable electronics, smart textiles, etc.

**Ebenezer Kofi Howard** is a full professor at KNUST with over 22 years of university teaching and research experience, specialising in Textile Art, Design Technology and Art Education with a focus on Design Thinking and Innovation, Sustainable Design Practice, and Curriculum Development. He is currently the HoD of the Department of Industrial Art and Vice Dean, Faculty of Art, KNUST.

**Dr. Timothy Crentsil** is a Senior Lecturer and the former Dean of the Faculty of Creative Arts and Technology and has served twice as Head of the Department of Fashion Design and Textiles Studies. He acts as Kumasi Technical University's liaison coordinator for the Commission of Technical Vocational Education and Training (CTVET). Dr. Crentsil holds a Bachelor of Arts Degree (Textiles option), a Master's degree in Art Education (Researched), and a Ph.D. in Art Education, all from Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi. His research interests encompass art and art-related businesses, fashion and textiles, technical vocational education and training (TVET), as well as private enterprise development. He has authored several articles in local and international peer-reviewed journals and has participated in numerous local and international research conferences.

**Charles Frimpong** is a full professor with the Department of Industrial Arts and also Dean of the Faculty of Arts. He has gained huge experience from the number of years he has lectured in the textile field and is one of the most experienced lecturers in the textile industry in Ghana

**Dr Theo Hughes-Riley** is an Associate Professor in Electronic Textiles where he acts as a research lead for a number of projects within the Advanced Textiles Research Group (ATRG). Dr Hughes-Riley's career has primarily concentrated on technology development with a strong multidisciplinary focus, exploiting his background in physics and experience with electrical engineering to address challenges in other fields. His current work focusses on the development of electronically active textile (E-textile) devices.

## Table of Contents

$\text{Ti}_3\text{C}_2\text{T}_x$  MXene offers several benefits, making it a good resource for conductive textiles. Textiles enhanced with  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes are applied in wearable electronics, especially for biomedical sensor manufacturing towards health monitoring. This review expounds on integrating  $\text{Ti}_3\text{C}_2\text{T}_x$  MXenes into textiles for biomedical purposes. Findings reveal that advanced sensors obtained from  $\text{Ti}_3\text{C}_2\text{T}_x$  MXene-integrated textiles are promising materials for smart healthcare.

G.K. Fobiri\*, E.K. Howard, T. Crentsil, C. Frimpong, T. Hughes-Riley

## Advances in $\text{Ti}_3\text{C}_2\text{T}_x$ MXene-integrated Conductive Textiles for Wearable Biomedical Sensors in Health Monitoring

