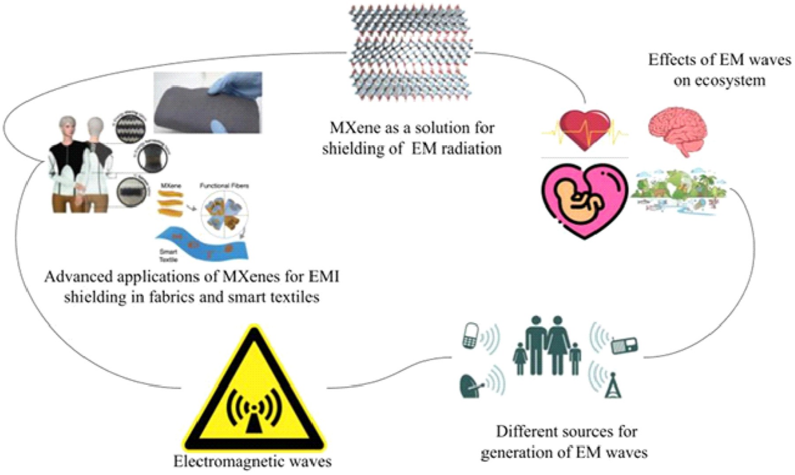

A Mini-Review On MXene Based Textiles For Electromagnetic Interference Shielding Application

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Abstract

The proliferation of smart, compact, and highly integrated electronics resulted in new pollution termed electromagnetic interference (EMI). Therefore, flexible and lightweight shielding materials are considered important for controlling the catastrophic effects of electromagnetic waves. In this regard, MXene-based textiles (M-textiles) have been proved to be efficient for shielding applications owing to their conductivity, mechanical flexibility, easy coating capability, etc, whose applications range from everyday clothes to aerospace, from protective to automotive, and so on. This paper engirds from the basic theory of EMI shielding to the latest research in M-textiles covering in detail the synthesis protocol and mechanisms. Based on these developments, this review aims to impart certain valuable insights, multifunctional applications, and advancements in M-textiles in this field.

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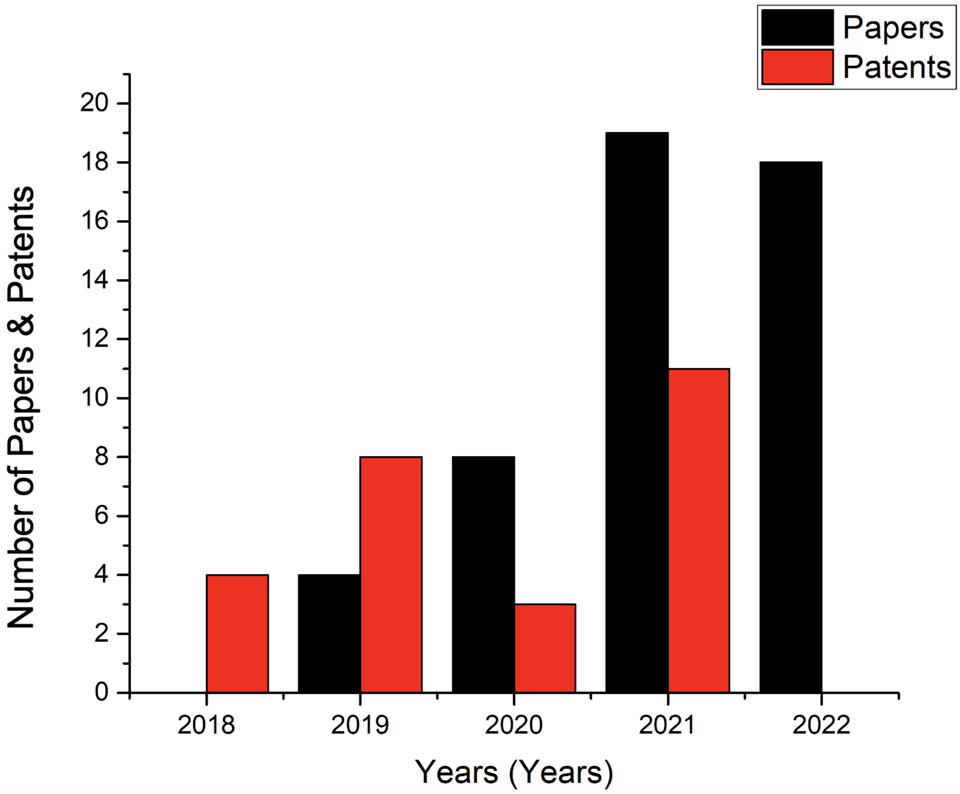
Introduction

The reign of commercial fifth-generation networks and the considerable rise in the count of wireless Internet of Things (IoT) devices operating within a wide range of frequencies critically demands communication stability and security with no EMI[1]. EMI is an electromagnetic emission that interferes with the surroundings or other electrical or electronic equipment, thereby impeding its proper performance. They are induced naturally or from manmade sources, which include the sun, the earth's magnetic field, radio signals, communication devices, or even vehicle traffics[2]. It results in operational faults, or even complete failure of the device, data loss, and possesses a disastrous effect on living beings and the environment[3]. Certain studies show that long-term exposure to such radiation severely affects human tissues, and can even affect the normal functioning of bio-electronic devices like pacemakers[4]. At present, there is an exponential rise in EMI due to the growing number of wireless devices and systems, including cell phones, Wi-Fi, Bluetooth, ZigBee, WiMAX (Worldwide Interoperability for Microwave Access), and GPS (Global Positioning System). EMI management spans a huge range of solutions for both active and passive devices in order to minimize emissions and to make the equipment less vulnerable to external interference through proper designing of equipment. Filtering is one of the common and also direct approaches to getting rid of unwanted signals. It usually starts with an AC line filter, which keeps unwanted signals out of the power supply and powered circuits preventing the addition of internal signals to the source. Shielding, on the other hand, is the most common method of containing radiation or coupling in source or victim devices, and it usually involves encasing the circuit in a totally sealed enclosure, such as a metallic box. Shielding is considered significant as the electromagnetic waves are reflected into the enclosure while also taking up the waves that are not reflected. The goal is to eliminate EMI or greatly suppress it so as to avoid interference, which paved the way to fabricate shielding fabrics. In this regard, numerous EMI shielding fabrics have been developed, amongst which M-textiles are demonstrated to be the best because of their combination of properties like least density, high electrical conductivity, Joule heating capability, and layered structure and surface polarity[5].

Numerous works have been carried out for developing materials for shielding applications which include metals, foams, laminated structures, conductive fabrics, composites and so on[6]. Since there is a high rise in the demand for lightweight and flexible structures, textile-based materials have mostly opted as they owe comfort, breathability, and sustainability to various shielding applications. Moreover, this becomes very important in this century as a plethora of wearable functional gadgets are highly demanded. These textiles find applications not only in daily wear apparel but also in upholstery as well as industrial textiles such as e-textiles, smart textiles, or protective textiles. Upholstery fabrics, such as curtains, can give the finest protection against EM radiation in structures that require defense, such as military and banking facilities. Although it is accepted that MXene is well established among various EMI shielding materials, the research based on them is still in its infancy. As far as we are aware, there is no published review of different M-textiles for EMI shielding applications. This review discusses the recent progress on M-textiles for EMI shielding applications, including their synthesis protocols, mechanisms, health effects, multifunctional applications, etc. Moreover, challenges and future prospects are also discussed, which will help the researchers and technologists who work in this area to improve their knowledge.

This paper analyses the recent and relevant reviews published and patents established on MXene-based Multifunctional EMI shielding applications and is plotted in the Graph. A period of five years from 2018 to 2022 (Science direct & Google Patents) is considered for investigating the recent progress as well as the current relevance of the above topic. It is clearly understood from the graph that the MXene-based EMI shielding applications are worth exploring since the number of papers and patents are found increasing over these years. A major rise in the number of papers published is during the year 2021-2022. This points out the current relevance of the subject.



Mechanism of shielding

When an electromagnetic wave passes through a shielding material, they interact with the material in three different ways. As shown in figure 1, the phenomenon of interaction or the mechanisms are namely reflection, absorption, or multiple reflection mechanisms. The mechanism of shielding by reflection helps in the bouncing off of radiation from the shielding materials and is also considered the primary shielding mechanism[7]. However, these reflected radiations may be undesirable to the environment as well as to living beings, and hence absorption mechanism for shielding is more preferred to reflection. The absorption mechanism is increased with increasing electrical or magnetic dipoles of the shielding material, due to its interaction with the magnetic field of EM waves. The interaction between electric dipoles in the material and the electric field in the radiation boost absorption through electrical polarizability[8]. Apart from reflection and absorption, multiple reflections are the third mechanism of electromagnetic shielding, representing the internal reflections within the shielding material.

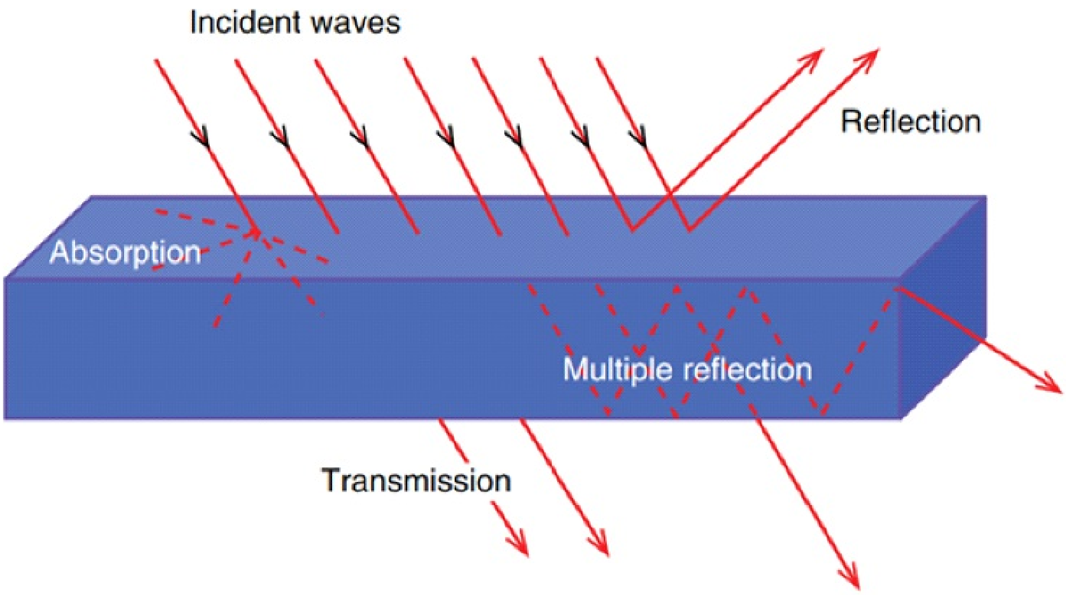


Figure 1: Schematic representation showing mechanism of EM shielding

A set of equations were formulated by Schelkunoff using a transmission line analogy, stating that the shielding effectiveness of a plane wave (SE) can be expressed as the sum of all the losses which includes losses by absorption (A) and reflection (R), and multiple reflection correction factor (B). It is given as[9]

SE= A+ R+ B and the defined unit is decibel (1)

where A is the absorption loss, which is considered as the secondary mechanism of EMI shielding. The shield is required to have an electric and/or magnetic dipole to interfere with the electromagnetic fields in the radiation. The attenuation by absorption mechanism is proportional to the thickness of the shield and can be expressed as;

$$A = 20log_{10}\left(e^{\frac{ts}{\delta s}}\right) = 8.686\left(\frac{t_s}{\delta_s}\right)$$

The charges in a conductive object are pushed to oscillate at the same frequency as the incident wave when rays in the form of waves strike it. These forced oscillating charges act like antennas, causing surface reflection. Depending on the pattern, the signal wave may reflect in a variety of directions connected with a charge that oscillates in a signal. As a result, the signal is dispersed, and there occurs a signal loss by attenuation due to reflection and this reflection loss R is defined as;

$$R = -20log_{10}\left|T_{tot}\right| = 20log_{10}\frac{|1+k|^2}{4|k|}$$

Where k is the ratio of the intrinsic impedance of metal shield in ohm to the free space characteristic impedance. Reflection from an electromagnetic shield takes place when there is difference in the impedance of the wave in free space from the impedance of the electromagnetic wave in the shield. This reflection mechanism does not depend on the thickness of the shield, but is influenced by conductivity, magnetic permeability and frequency of the shield

In the depth of the medium layer, sequential signal losses also occur. This attenuation is caused due to successive multiple internal reflections. The multiple reflection correction factor accounts for the decrease in shielding effectiveness for shields with low absorption loss because of multiple reflections within it. This term is given by;

$$B = 20log_{10}\left|1 - \frac{(k-1)^2}{(k+1)^2} e^{\frac{-2t_s}{\delta_s}}\right|$$

EMI shielding comprises two regions, the near field shielding region and the far field shielding region. Electromagnetic radiation having high frequencies is able to penetrate only the near surface region of an electrical conductor. This is termed as the skin effect. The electric field of a plane wave penetrating a conductor is inversely proportional to depth into the conductor. The depth at which the electric field of a plane wave falls to 1/e of the incident value is known as the skin depth (δ). It is given by the equation[10];

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Where,
f = frequency,
μ = magnetic permeability = $\mu_0\mu_r$,
μ_r = relative magnetic permeability,
$\mu_0 = 4\pi \times 10^{-7}$ H/m, and
σ = electrical conductivity in $\Omega^{-1}m^{-1}$

It is understood from the above equation that the skin depth reduces as the frequency rises and the conductivity or permeability rises. The EMI Shielding Effectiveness of a given shielding material can be measured by different methods, which includes Open Field or Free Space Method, Shielded Box Method, Shielded Room Method and Coaxial Transmission Line Method[11]. The open field or free space method evaluates the practical shielding effectiveness of a whole electronic gadget by measuring the radiated emissions that escape from a final product. The Shielded Box Method is effective for frequencies below 500 MHz. It entails the use of a closed box with an opening, through which a shielding unit is inserted. This helps to record EM signals from both in and out of the box and the ratio between these signals indicates shielding effectiveness. Alternatively, the shielded room method involves two shielded rooms having a separating wall in between. One of the rooms contains testing equipment whereas sensors are carried in the other. This method is found suitable for measuring the susceptibility of a device. The last method is the Coaxial Transmission Line Method, which is a comparative technique to measure the shielding effectiveness of a planar material. It consists of a reference-testing device and a load device. The voltage received by the reference device is recorded at varying frequencies. The load-device is subsequently installed, and voltage readings are taken in the same manner. By comparing the readings of the reference and load devices, the shielding effectiveness is determined.

Health effects of EMI

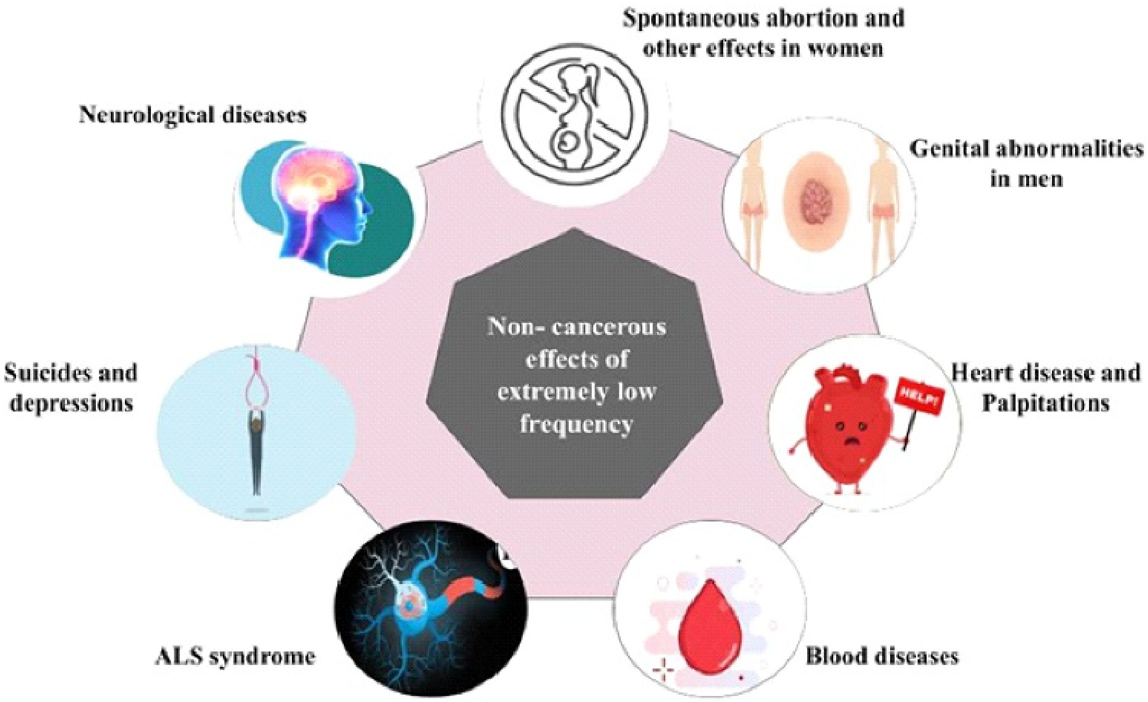
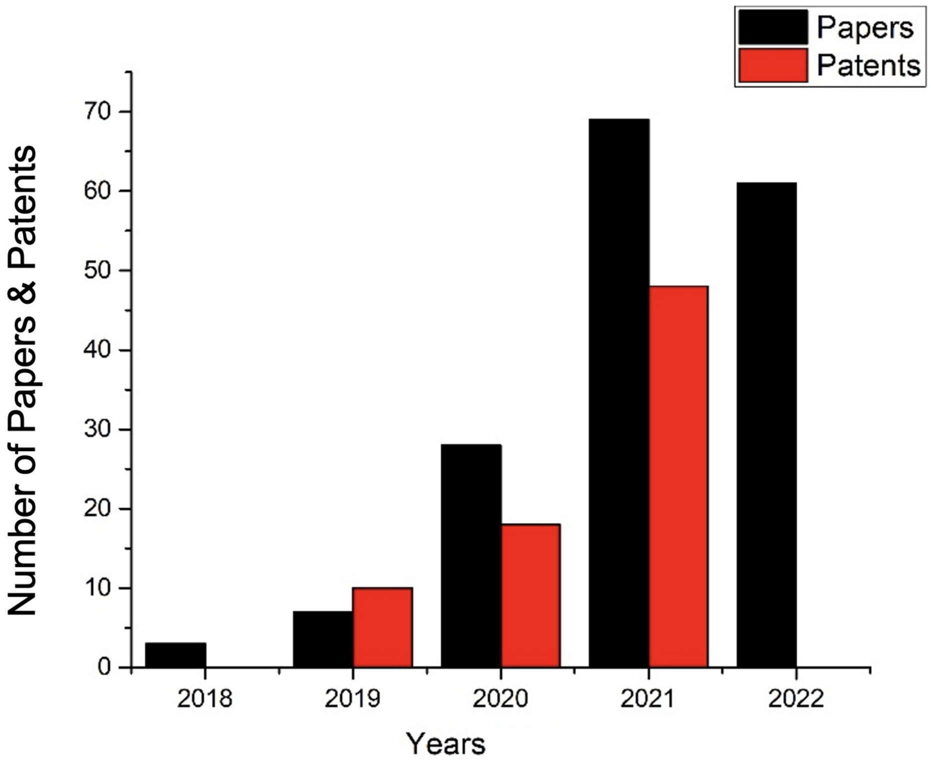


Figure 2: Effects of EM radiation on human health

On account of the increased use of electronic appliances, the shielding of other devices, and of Human beings from EM waves are a very crucial issue in this current scenario. Even though EM waves are harmful to both electronic devices as well as to human beings, it is practically impossible to reduce the application of electronics in our daily lives. EM waves can interfere with or damage electronic devices, changing the voltage in the proximity so that the components like regulators, switches, and circuit boards in electronic equipment turn faulty. These radiations have severe effects on living beings as they can penetrate into human cells and can even cause damage to DNA. When cells are exposed to EM radiation, these DNA strands can be cleaved causing several problems. Any changes or damages to DNA can affect the functioning of living cells, which may proliferate and eventually cause cancer. Moreover, several studies have reported stress, headache, fatigue, anxiety, reduced learning potential, impaired cognitive functions, and poor concentration in being vulnerable to electromagnetic radiation[4]. Several studies were carried out regarding the biological effects of EM radiation from different domestic appliances. It was found that the users are continuously exposed to such emission from different electronic gadgets like television, microwave ovens, heaters etc. A person watching or working in front of a television or computer is continuously affected by the E and H fields of electromagnetic radiation resulting in the flow of electricity through his or her body, which is primarily associated with the generation of heat within the body. These heats up the tissues and thereby alters the whole bodily functions. Since the 1970s, microwave ovens have been used all over the world for a number of purposes. However, it was found that a prolonged exposure to microwaves adversely affects the tissues of liver as well as bone marrow[12].

The graph below represents the number of papers and patents related to the health effects due to electromagnetic radiation. The severity of the induced radiation is well explained in each of the papers and is found more acceptable over these years. A period of five years from 2018 is considered for the brief analysis and all these studies highlight the necessity of having a proper electromagnetic shielding mechanism. The materials used for EMI shielding are shaped so as to form an enclosed structure, providing isolation to the emitter or receiver of electromagnetic interference, and are fabricated taking into consideration the requirements for a specific EMI application. The emission of high-frequency electromagnetic radiation from the device is prevented, or the device is protected from drifting radiation by a metal shield and cover. The commonly used metals for this purpose were brass, aluminum, silver, nickel, stainless steel, metalized plastics, and conductive carbon/graphite composites. But, the brittleness of carbon/graphite, the low impact resistance of Aluminium, the high density of stainless steel, and all the above, the corrosive nature of metals limits their applications in the process of EMI Shielding. This made researchers extend their works to materials such as blends, porous materials, ceramic materials, etc. Recently, EMI shielding textiles have also achieved significant recognition owing to their weightlessness, high flexibility, and good conformability. They are of great practical applications due to their strong water repellency, which ensures their high durability under harsh, wet, or corrosive environments. EMI shielding textiles could be well suited for all-weather outdoor equipment such as mobile communication systems, signal stations as well as anti radiation clothing.



Materials for EMI shielding

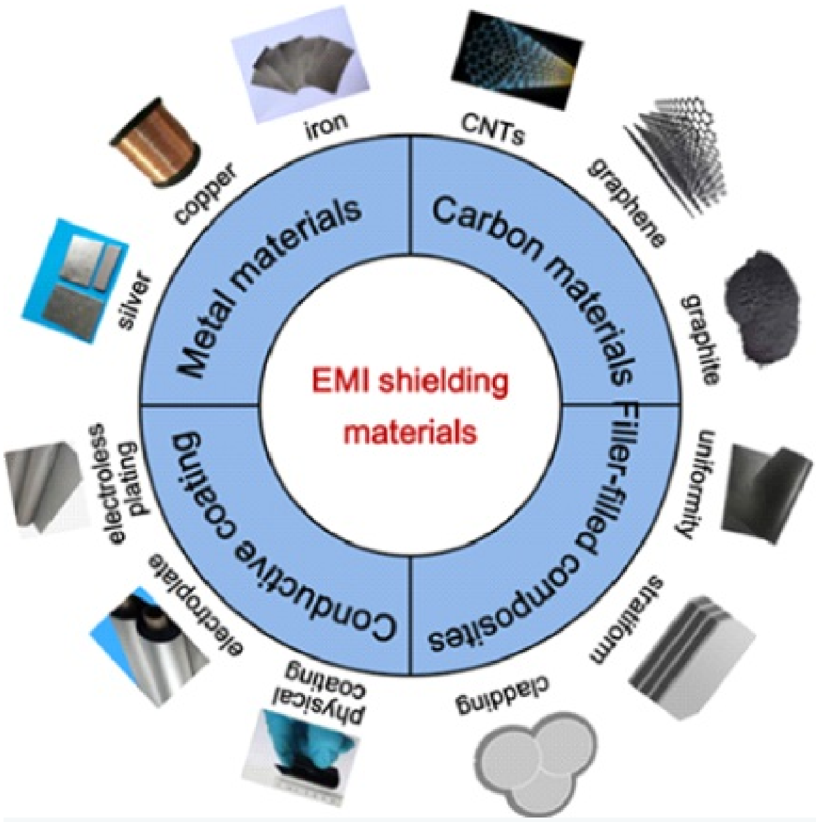


Figure 3: Different materials for EMI shielding[13]

Electronic equipment is considered electromagnetically compatible with its surroundings when it doesn't cause interference with other appliances or itself and is not concerned by emissions from other devices. Hence, a good electromagnetic shielding material is destined to prevent both entering and leaving electromagnetic interference. The power loss occurring as a result of the interaction between incident radiation and the shielding material is referred to as shielding effectiveness, expressed in decibels, marks the gaining of considerable attention to different materials for EMI shielding. These materials comprise metals, carbon, ceramics, cement, polymers, hybrids, and composites[14].
Metals are good electrical conductors and can absorb, reflect and transfer electromagnetic interference. Conventional metals like Aluminium, Copper, Nickel, and others were initially used as barriers against EM waves, however, the increased density and low oxidation resistance of metal limits its practical application as EMI shielding materials. Polymeric EMI shielding materials, hence, have gained considerable importance over conventional EMI shields made up of metallic materials, owing to their ease of processing, lightweight, enhanced corrosion resistance, and economical fabrication methods. An electrically conductive EMI shielding polymeric composite is generally fabricated by mixing any conductive filler like metallic powders, metal flakes, metal nanowires, carbon black, graphite, graphene, and carbon nanotubes into the polymeric matrix. Conducting polymer composites having characteristic features of excellent electrical and optical properties have also been used in different applications of EMI shielding. A number of inherently conductive polymers were studied during the late 70s including polyaniline and polypyrrole. But the lack of processability and difficulty in transforming them into usable structures. The research was carried out to overcome this challenge to introduce the use

of textile substances as structured reinforcement for the conductive polymers. For instance, a workshop was conducted by Nakoliev et al[15], polymerizing Pig and PAN: onto nylon, polyester, and quartz fabric and forming flexible and conductive textile structures without compromising the mechanical and tactile properties of the fabrics. Carbon materials, which include coke, graphite, graphene, CNTs, etc. are not only electrically conductive but also show exceptional absorbance of electromagnetic radiation over different frequencies. Moreover, their extremely low density, wide availability, magnificent weather resistance, and chemical stability make carbon materials a notable candidate among numerous materials for EMI shielding applications. Hybrid nanocarbons and porous nanocarbons are synthesized for EM shielding by improving the surface area and in addition, decreasing the impedance mismatch between the material and the air surrounding it. This in turn reduces the losses by reflection, thereby enhancing the absorption loss, which is considered the primary mechanism for shielding using carbon. Several attempts have been made to fabricate inks for the purpose of shielding which can be used in places where solid or powdered materials cannot be coated on the sample efficiently. Conductive inks prepared from metals like gold, silver, and copper and different conductive polymers have been analyzed, stability, cost, and oxidation are found to be the drawbacks associated with some of these inks. It is equally important to ensure that the ink does no harm to the substrate or surface while getting coated. There exist different methods for printing like stamping, drop-casting, or inkjet printing in order to utilize and examine these inks for multiple applications. Ceramics are another type of EMI shielding material but are not very common as metals or carbon due to their relatively low conductivity, polarizability, and magnetic behavior. So, ceramics are generally used along with carbon or metals as ceramic composites for the purpose of EMI shielding. However, certain ceramics like Ti3AIC2 withstand extreme temperature conditions and are found suitable for high- temperature shielding applications. MXenes are an emerging class of ceramics, which are two-dimensional inorganic compounds comprising layers of transition metal carbides, nitrides, or carbonitrides, each layer having a thickness of a few atoms. They were discovered very recently in 2011 by Barsoum and Yury Gogotsi at Drexel University. The reason for the interest of researchers in the different aspects of MXenes lies in its fascinating properties which include high electronic conductivity as well as optical transparency and apart from EMI shielding, applications for these materials were greatly found in energy storage, polymer composites, and many others. They are generally synthesized from MAX phases with the general formula M+1AXn (n=1-4). The three common MAX phase structures are M2AX, M3AX2, and M4AX3, where M represents transition metal, A, an element of group 13 to 15 of the periodic table, and X carbon and/or nitrogen. Consequently, MXenes commonly have three structures: M2XTx, M3X2Tx, and M4X3Tx, and based on the different M and X elements, they can also be sorted as mono-metal MXenes, double-metal (M′ and M") MXenes, and double-X (C and N - carbonitrides) solid solution MXenes. It is demonstrated that the mono- X MXene has better EMI shielding performance than the double-X MXene (carbonitride)[16]. The EMI shielding performance of MXene films having thicknesses ranging from nano to microscale has been investigated and concluded that the large surface area, polarizability, and conductivity make MXenes potentially attractive for EMI shielding, with good shielding effectiveness values not less than 50 dB as reported by various research groups[17].

Case studies

Several materials possessing multifaceted characters have influenced considerable scientific and technological interest for the absorption of high-performance electromagnetic waves and the shielding of electromagnetic interference. MXenes are one such material found to have great potential in EMI shielding. It has a distinctive multilayer microstructure, large specific surface area, good electrical conductivity and metal-like properties, contributing to the formation of highly efficient EMI shielding materials[18]. In the recent past, various materials like intrinsically conducting polymers, nanowires, carbon nanomaterials of graphene sheets, and carbon nanotubes in combination with MXenes have been strategically explored for the development of novel electromagnetic attenuation materials[8].

One of the latest works on MXene based EMI shielding material highlighted the 2D/ 1D/ 0D construction of Ti3C2Tx/CNTs/Co nanocomposites by microwave-aided, in-situ carbonization and electrostatic assembly process. The CNTs/Co nanocomposites were introduced on 2D Ti3C2Tx MXene sheets to form laminated Ti3C2Tx/CNTs/Co nanocomposites with an enhanced EMI shielding effect of 110.1dB. This study conducted by Xiang et al[19] reveals that the performance of electromagnetic wave absorbance was improved by the interdependent effects of the conduction loss due to the electronic transport in the conductive network of 1D CNTs and 2D Ti3C2Tx, and the magnetic loss due to the ferromagnetic resonance of 0D Co nanoparticles. The EMI shielding values as shown in the figure [4] revealed that with addition of the CNTs/Co content the shielding efficiency initially had a rise and then dropped. The Ti3C2Tx/CNTs/Co film loaded with 10% weight of CNTs/Co exhibited the maximum value for shielding effectiveness at 62.0dB. In addition to excellent EMI shielding efficiency, flexibility, hydrophobicity, enhanced photo thermal conversion performance was also exhibited by the resulting material.

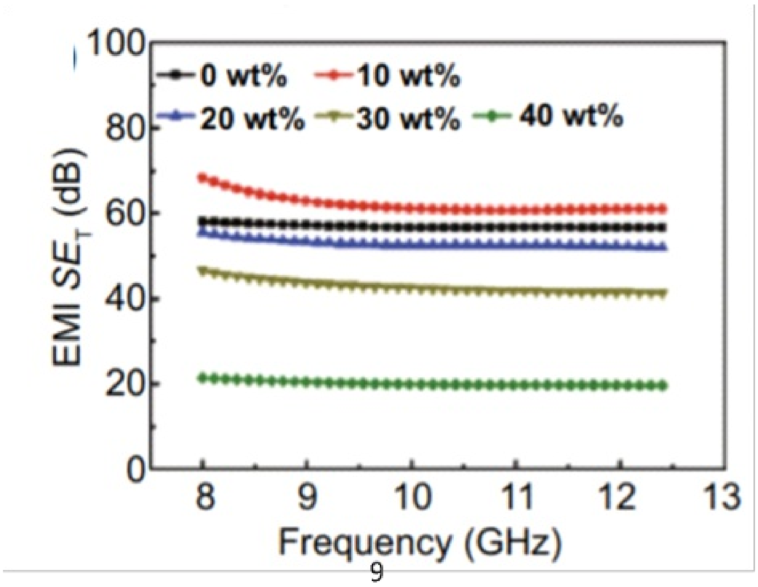


Figure 4: The SE vs frequency plot[19]

Although flexible and multifunctional textile-based electronics hold promise for wearable devices, integrating superior conductivity into textiles without compromising their inherent flexibility and breathability remains a difficulty. A recent study by Zhang et al[20] developed an efficient technique for converting common cotton fabrics (CF) to EMI shielding textiles. Initially, MXene nanosheets were synthesized by an etching process using HCl and LiF and the as-obtained inks were coated on the surface of treated CF by the process of spraying. The MXene loading on CF was 2, 4, and 6wt% which were tuned by regulating the spray drying cycles. Results revealed that adjusting the spraying cycles tuned effectively the conductive networks and hence the SE values. Shielding performance of up to 36dB and conductivity of 5 Ω sq^{-1} with reflection dominant mechanism was reported at 6 wt% MXene loading in X band frequency range. The shielding performance will be enhanced due to multiple interfaces scattering of EM waves on the surface of the fiber, owing to its bark-shaped morphology. Moreover, it also accounts for reduced contact resistance of the fibers resulting in good piezoresistive sensing capability along with good joule heating performance of the fabrics.

Following the recent trend of multifunctional textile-based electronics with inbuild energy storage, joule heating, and EMI shielding, Zheng et al. synthesized a multifunctional RGO-Ti3C2Tx MXene decorated cotton textile. Cotton fabric is used here as the substrate for RGO-Ti3C2Tx MXenes deposition since they have many oxygen-rich functional groups and was prepared by the method of dip-coating followed by spray-coating. The synergetic effects between reduced graphene oxide and MXene resulted in good EMI shielding ability of around 29.0dB under x-band as well as excellent joule heating performance. These RGO-Ti3C2Tx MXenes decorated cotton fabrics find potential applications in wearable electronics and multifunctional smart textiles[21].

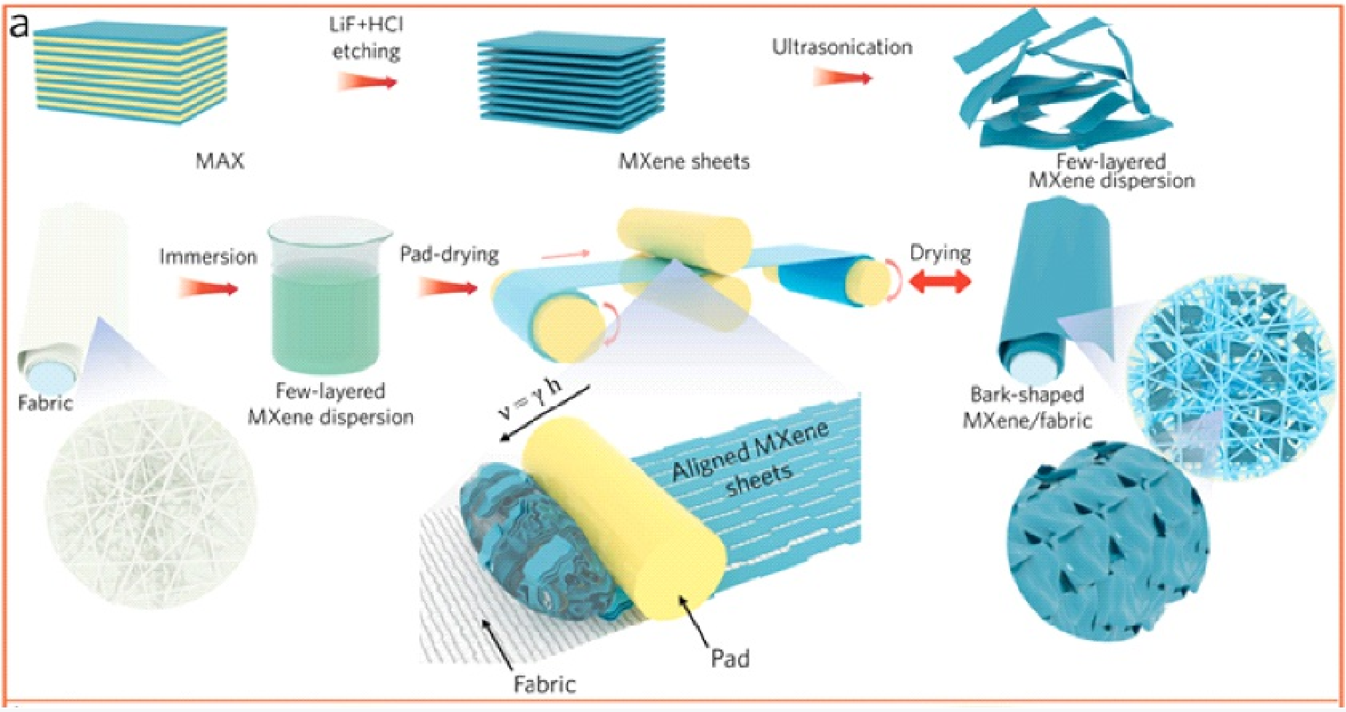


Figure 5: Schematic illustration of the preparation of bark-like MXene decorated fabrics [20]

In another work by Wang et al.[22], a flame retardant aramid nonwoven textile was fabricated using MXene for high electromagnetic interference shielding performance with 35.7 dB. This study shows the fabrication of a new generation of safe wearable MXene-based heaters with good EMI shielding, allowing for multiple EM wave reflections and absorption while maintaining low thermal conductivity. In addition, these composite fabrics exhibit magnificent electrothermal and photothermal conversion properties due to the interlacing conductive network, formed by nonwoven textile and stacked

MXene nanosheets.

Wang et al.[23] in their work developed extremely conductive and hydrophobic textiles with significant shielding efficiency and enhanced Joule heating performance by layering in situ polymerized polypyrrole (PPy) modified MXene sheets onto poly(ethylene terephthalate) textiles followed by a silicone coating. The fabricated textile owed a conductivity of ≈1000 Sm−1 along with an extraordinary shielding efficiency of around 90 dB at 1.3 mm thickness. These PPy modified MXene sheets when compared to the normal MXene sheets possess numerous PPy particles as identified from the TEM images given in figure 6 a, b. Figure 5 differentiates the microstructures and surface morphologies of pristine textile, M- textile, and silicone coated M-textile using SEM. The synthesized fabric structure is maintained well and the oversized pores among the fibers are not congested after modifying it with the PPy/MXene ink as shown in Figure 7a,c. In fig 7b, d, the ink modified textile has slightly irregular fiber surfaces conformally overlaid with MXene sheets and tiny nanoparticles contrary to the smooth surface of pure PET fibers.

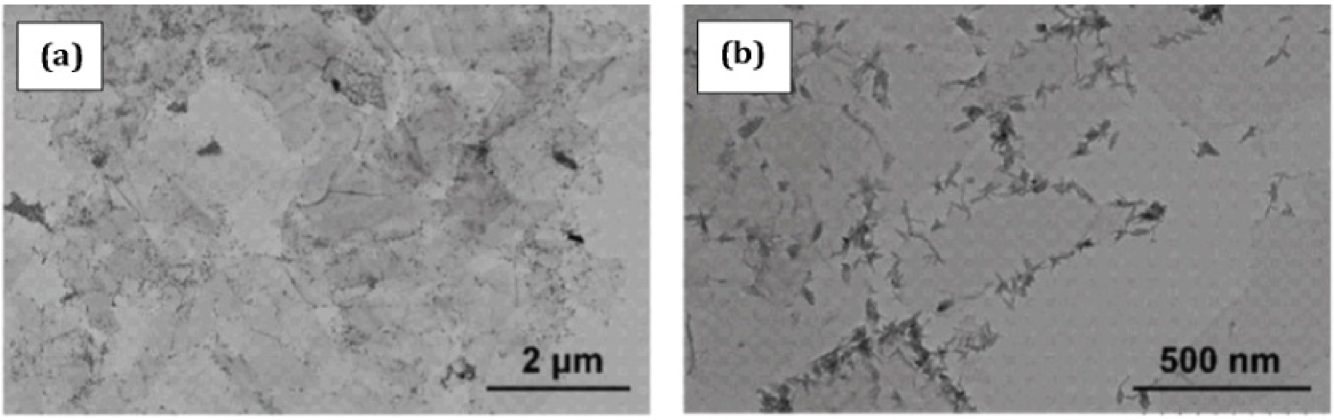


Figure 6(a,b): TEM images of PPy/MXene [23]

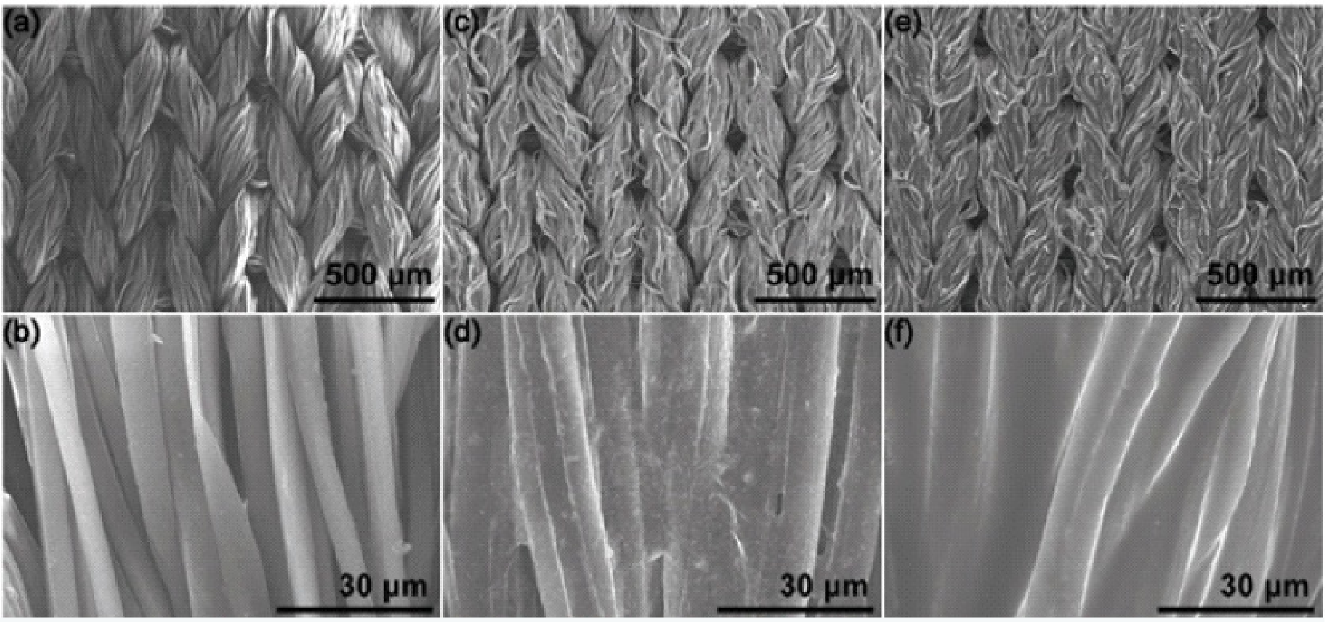


Figure 7: SEM images of a,b) pristine textile, c,d) M-textile, and e,f) silicone-coated M- textile [23].

In a work reported by Cheng et al.,[24] EMI shielding coating on cotton textile was fabricated by the simple method of solution impregnation followed by dip-coating method, involving three layers of poly acetimidate (PEI), ammonium polyphosphate (APP), and Ti3C2Tx. This fabric from cotton slowly achieved better EMI shielding performance by coating it with increasing amounts of Ti3C2Tx. When the content of the $Ti_3C_2T_x$ sheet was taken as 5.2 mg/cm2, an enhanced electrical conductivity of 670.3 $S{\cdot}m^{-1}$ and shielding effectiveness of 31.04 dB was accomplished in the X-band with an absorption-dominated process. The electromagnetic interference shielding mechanism was majorly based on absorption in this case. The average shielding effectiveness value of FC-5.2Ti3C2Tx range up to 31.04 dB while the amount of Ti3C2Tx was 5.2 mg/cm^2 by an absorption-dominated mechanism, allowing it to dissipate 99.9% of the electromagnetic wave. In this study, the conductivity of the Ti3C2Tx coating for the cotton fabric is estimated and analyzed by measuring its electrical conductivity and SE. It is evident from figure 8a that the electrical conductivity of the sample increased with the rise in the addition of Ti3C2Tx content in the MXene coated flame retardant cotton textile composite than the as-fabricated PC & FC. This variation is analogous to the EMI SE values as shown in figure 8b. Here, the total EMI shielding effectiveness, absorption, and reflection of the sample in the x band were investigated, indicating that the Ti3C2Tx coated MXene coated flame retardant cotton fabric composite exhibits absorption dominant EMI shielding mechanism. The resultant cotton fabric not only possesses electromagnetic shielding properties but also, is highly flame retardant and has the capability to be used as critical heating material.

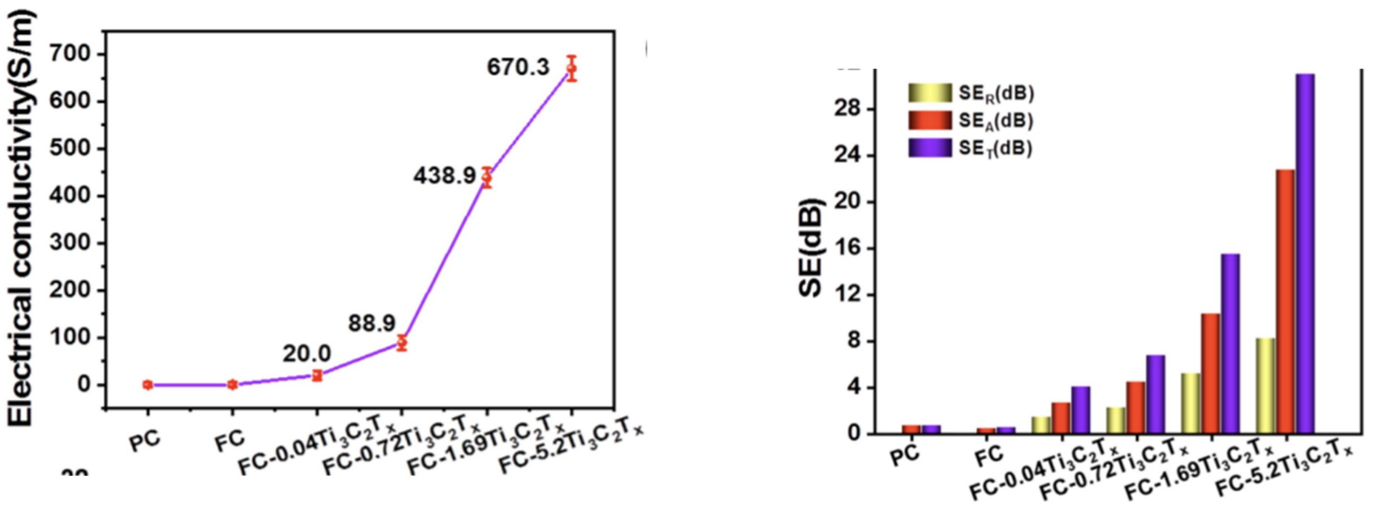


Figure 8: Electrical conductivity (a) EMI shielding performance (b) of samples in X-band; ratios of SER/SEA [24]

In a study conducted by Zhang et al., MXene-based lightweight non-woven fabrics were synthesized for absorption dominant EMI shielding. The different properties of the fabricated textile made them effectively shield electromagnetic waves. These properties include high conductivity, porosity, and layered structure of the non-woven fabric. The developed flexible, lightweight EMI shielding materials with wave absorption-dominated properties may cover a broad area of any shape, contributing to the development of a wide range of EMI-shielding materials[25].

Despite the fact that high-performance electromagnetic shields have been widely developed in response to increased electromagnetic interference pollution, research has been conducted to develop novel EMI shields having renewable biomass substrates in order to introduce new functionalities and expand their application scenarios. Jia et al.[26] synthesized long-lasting MXene-decorated EMI shields by depositing highly conductive Ti3C2Tx MXene networks onto a wood-pulp fabric grid (FG) and then applying a hydrophobic methyltrimethoxysilane (MTMS) coating with multi-scaled roughness using a simple vacuum-filtration and sol-gel process[20]. The fabricated MTMS-M/FG exhibited greater EMI-shielding effectiveness up to 90 dB along with outstanding hydrophobic properties having a water contact-angle of ~132-138°.The distinct wetting behaviors of different fabric grids (FG) are shown in Figure 8a. The water contact angle (CA) of pristine FG was around 80°, but after coating with a hydrophilic MXene layer, the CA of M/FG reduced to 65°, owing to the presence of polar functional groups such as -OH and -F on the MXene sheets. Conversely, the hydrophobic methyltrimethoxysilane (MTMS) coating having a low value of surface energy and high surface roughness resulted in MTMS-M/FG having an increased CA greater than ~132°, reaching the highest value of 138°, and the water droplets could easily drop down its surface without any adhesive force. The given schematic clearly states the conversion from hydrophilic to hydrophobic and the excellent water-resistant performance of MTMS-M/FG. It also has exceptional mechanical flexibility and exemplary structural stability resulting in improved performance stability. Moreover, the MTMS-M/FG exhibited magnificent thermal stability as well as an adequate low-voltage-driven Joule-heating performance with the saturated temperature of ~40-95°C at a constant voltage ranging between 1-4 V.

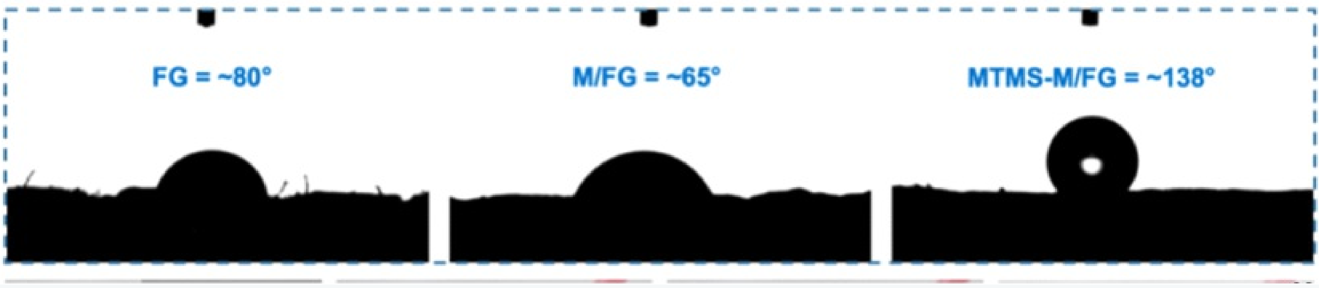


Figure 9: (a) Water contact angle measurements of pristine FG, M/FG and MTMS-M/FG [26].

In a study conducted by Guang et al.[27], a lightweight, wearable, and durable PANI/MXene/CF fabric with excellent EMI shielding performance were manufactured by layer-by-layer spraying technique assembly method as given in the figure (9). The sample is prepared by alternately arranging PANI of positive charge and negatively charged MXene sheets on carbon fiber (CF) fabric by L-b-L assembly as shown in the figure. It was evident from the results that the 0.55 mm-thickness fabric exhibited a good electrical conductivity of 24.57 S/m and high electromagnetic shielding efficiency of 26.0 dB, with an absorption-based shielding mechanism. Besides, the synthesized fabric shows attractive Joule heating performance (113 °C) with low voltage (5 V), a quick response time (< 10 s), outstanding heating stability, and effectual de-icing as well as potential thermal stealth behavior. The resultant fabric is eco-friendly and produces no secondary electromagnetic pollution as it exhibits an adsorption-based shielding mechanism.

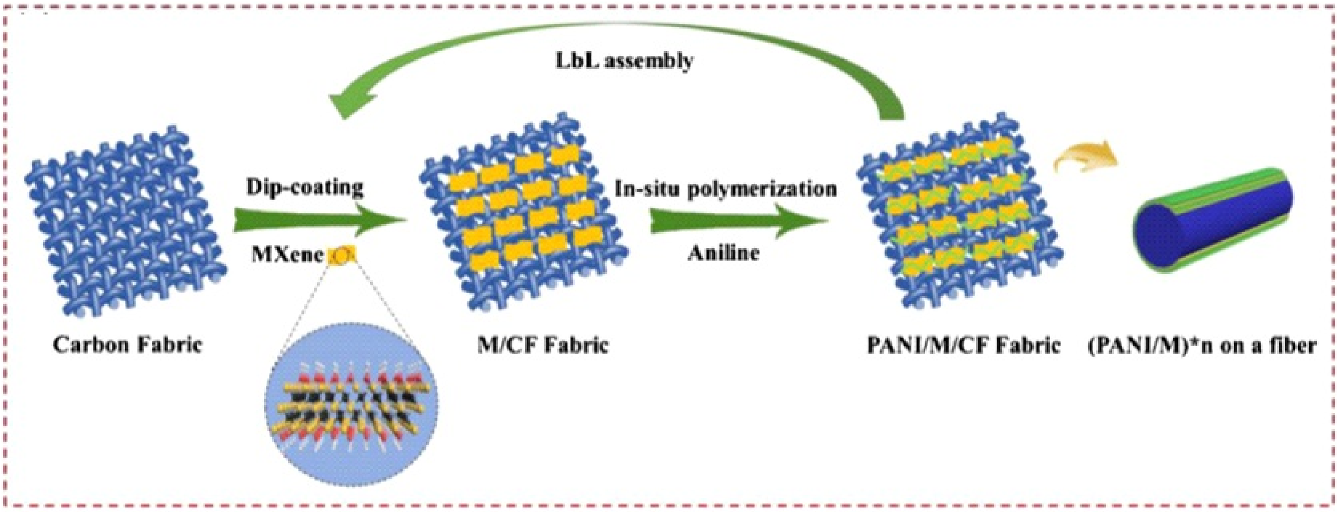


Figure10: The schematic illustration for the manufacturing process of PANI/MXene/CF fabric[27]

Stretchability and multifunctional heating capabilities are also highly appealing for wearable EMI shielding fabrics to confront the increasing electromagnetic pollution. Recently, Dong et al[28] conducted an experiment on stretchable MXene-coated thermoplastic polyurethane (TPU) fabrics by common uniaxial pre-stretching and spraying methods as the schematic given below, endowed with excellent EMI shielding properties of efficiency around 30 dB. This work provides a novel strategy for the flexible design of stretchable and multifunctional wearable shielding textiles for a special mass including pregnant women. The obtained sample performed a reflection-dominated EMI shielding mechanism. The delaminated Ti3C2Tx MXene nanosheet was obtained as colloidal suspension after undergoing the processes of etching with hydrofluoric acid and ultrasonic exfoliation.

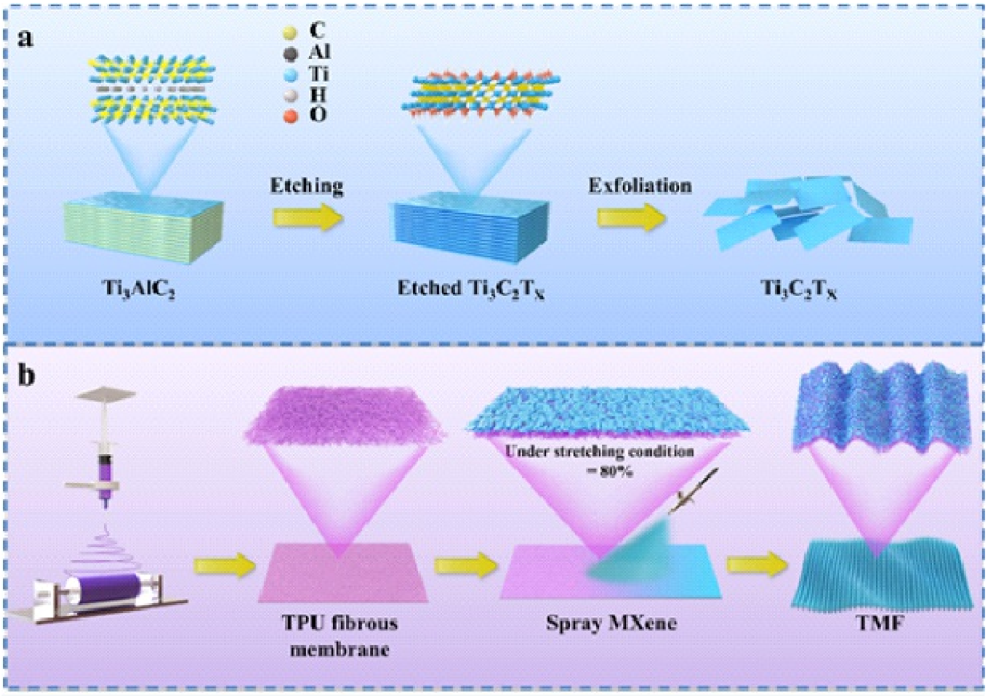


Figure11: Schematics of the fabrication techniques of (a) Ti3C2Tx MXene nanosheets and (b)

TPU/MXene fabric with a delicate micro wrinkle structure[28].

Researches were intense on developing EMI shielding devices with efficient adherence to fabrics for applications of implantable or wearable electronics. A group of scientists led by Yuri Gogotsi recently reported an MXene-coated fabric that can block almost all electromagnetic waves along with providing a lightweight option for blocking EMI in wearable devices. In this study, regular cotton and linen textile materials were dip-coated in an MXene solution, specifically, titanium carbonitride. They found that this thin few-atoms- thick fabric, when converted into a shielding material, absorbs and reflects waves rather than reflecting them, blocking EMI with a shielding efficiency of 99.9%. MXene flakes suspended in solution get attached to cotton and linen fibers because of their electrical charge, producing a durable coating. Apart from shielding against EMI, these fabrics may also help in building protective suits for people working in environments with dangerously-high levels of electromagnetic fields.

Several attempts have been made to incorporate MXene into polymer matrices in order to create MXene/polymer composites. Several nacre-like MXene/cellulose composites have been developed for a variety of applications and have proven to be an effective EMI shielding materials. Table 1 summarizes the EMI shielding capability of several MXene textile interfaces.

Table 1: Electromagnetic Interference shielding performance of different MXene textiles

MATERIAL	THICKNESS (mm)	EMI SHIELDING EFFICIENCY (dB)	REFERENCE
Ti3C2Tx/CNF	0.047	24	[29]
Ti3C2Tx/CNF/CNT	0.038	38.4	[30]
Ti3C2Tx/Cellulose	0.0861	43	[31]
Ti3C2Tx/Aramid fiber	0.017	28	[32]
Ti3C2Tx/CNF	0.035	40	[33]
Ti3C2Tx/Carbon Fabric	0.25	43.2	[34]
Ti3C2Tx/CNF/Ag	0.046	50.7	[35]
Ti3C2Tx/Cotton Fabric	0.33	36	[36]
Ti3C2Tx/PET/ PPy	1.3	90	[37]
Ti3C2Tx/Silk	0.12	54	[38]

Challenges

The MXenes system has some challenges to consider for future research. Although more than 30 different MXene synthesis methods have been found, only a few MXenes such as Ti3C2, Ti2C, Mo2TiC2, Mo2Ti2C3, and Ti3CN have been investigated. Understanding the effects of constituent composition, layer structure, and arrangement of transition metal on MXene EMI shielding properties and other MXenes need to be investigated. In addition, because of the vast family, MXene with novel atomic compositions or new crystal lattice arrangements such as M5X4 can be synthesized and studied. However, the Synthesis of MXenes is still very difficult due to their instability after exfoliation. Furthermore, greener approaches for high yield synthesizing of high-quality MXenes also need to be addressed. Additionally, some efforts have been focused on developing multifunctional EMI shielding materials at the present stage. For instance, the properties of outstanding EMI shielding, Joule heating, self-cleaning, etc. The development of multifunctional materials that combine EMI shielding performance with other functions such as anti-corrosion, good heat dissipation, and hydrophobicity is a direction worth exploring. MXenes demonstrated remarkable electrical conductivity and excellent EMI shielding efficiency. They are also easy to process due to the abundant functional groups on their surface, but their stability is poor and they are easily oxidized. Besides, the force between MXene nanosheets is too weak to form a strong structure. Therefore, new methods for the preparation and anti-oxidation of MXene, as well as the design of the structure of materials urgently need to be developed. MXenes that are highly conductive typically show a huge reflective contribution to the electromagnetic interference shield and can lead to secondary contamination. To counter this, structural designs and separation structures such as permeable foams and aerogels have been proposed. However, it is necessary to fabricate MXene shielding materials with various structural factors such as meta-structures that can significantly enhance the absorption of incident EM waves. Moreover, MXene's hydrophilicity is limited by the fact that their polymer composites or nanohybrids can only be produced in water environments. So as to expand the extent of structural design, it is required to fabricate and study MXenes, which have a hydrophobic surface and also its organic dispersion. The post washing procedures have to be done carefully after coating these textiles with nanomaterials as there is a chance for release of the same into the environment. This could pose a threat to the lives of the human as well as other living beings. The existing coating processes for textile substrates, such as in situ polymerization, electrochemical polymerization, electrostatic spinning, lamination, or printing, do not provide sufficient bonding. During wear or after washing operations, the coated textile loses its conductivity. As a result, the abrasion and washing resistance of fabrics coated with MXenes must be increased and hence in such circumstances, excellent binders should be used, which would be beneficial. So, it is highly advised to develop new effective ways for extending the endurance of nanocoatings on textiles to reduce the risk of exposure to nanomaterials released from nanocoatings. Another issue noted is the restacking tendency of MXene sheets. This self-stacking mechanism becomes very crucial when used for electrochemical applications where the transmission of ions reduces upon self-stacking.

Although the research on EMI shielding materials is very extensive, the underlying mechanism of how shielding materials interact with EM waves is still poorly understood. Thus, it is a development direction to study the EMI shielding mechanism with the aid of simulation software such as HFSS, CST, and COMSOL. MXenes research is still in its infancy, and there's plenty of room to learn more about the new MXene and its shielding since many of the nano-related achievements in the area of textiles exist only in the lab-scale and start-ups.

Conclusion

In this advanced era of technological revolution, electronic equipment is an inevitable part of daily lives but generates enormous electromagnetic energy negatively affecting both the endurance of electronic appliances by interfering with other neighboring components as well as the existence of living beings. Prolonged vulnerability to electromagnetic radiation creates a threat of different diseases such as nausea, eye irritations, cancer, and even detrimental effects on infant brain growth. In addition, electromagnetic waves also induce faults in the modern military system. The interaction between their intrinsic charge carriers and electromagnetic fields, which attenuate the electromagnetic radiation, is the principal function of EMI shielding, implying that EMI shield materials must have a reasonably high electrical conductivity. The 2D Ti3C2Tx MXene was introduced in 2016, as a material for shielding electromagnetic interference, after which it gained immense consideration in the research fields. MXenes could be at the front line of EMI shielding technology utilizing advantages of high specific surface area, reduced density, outstanding electrical conductivity, and lightweight features. At present, research on MXene-based EMI shielding material is mainly concentrated on 2D MXene films, composites, and 3D MXene aerogels[39] with exceptional EMI shielding efficacy. In order to defend against electromagnetic rays, a range of electromagnetic shielding composite fabrics have also been developed. Researchers have used a variety of methods to create electro-conductive textile fabrics that provide efficient electromagnetic shielding. To manufacture electro-conductive textiles for electromagnetic shielding, conductive particles such as copper, silver, or even carbon are put to textile material as a surface coating using appropriate procedures.These metalized textile textiles' shielding efficacy is primarily based on the idea of energy reflection. In many circumstances, such reflection phenomena result in undesired interference, and the performance of shielding material is found inadequate. However, MXene-based textiles (M-textiles) have been shown to be efficient for shielding applications owing to their different properties like conductivity, mechanical flexibility, easy coating capability, etc. In fact, many of the nano-related successes in the domain of M-textiles exist only in the lab-scale and start-ups, and hence there is a need for further research to learn more about the MXene and its shielding.

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