A review on MXene for energy storage application: effect of interlayer distance

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Abstract
To meet the energy needs batteries and supercapacitors are evolved as a promising candidate from the class of energy storage devices. The growth in the development of new 2D electrode materials brings a new revolution in energy storage devices with a comprehensive investigation. MXene, a new family of 2D metal carbides, nitrides and carbonitrides due to their attractive electrical and electrochemical properties e.g. hydrophilicity, conductivity, surface area, topological structure have gained huge attention. In this review, we discussed different MXene synthesis routes using different etchants e.g. hydrofluoric acid, ammonium hydrazine, lithium fluoride, and hydrochloric acid, etc showing that fluorine formation is compulsory to etch the aluminum layer from its precursor. Due to the advantage of large interlayer spacing between the MXene layers in MXene, the effect of intercalation on the performance of batteries and supercapacitors using MXene as electrodes by various sized cations are reviewed. Different MXene hybrids as supercapacitor electrodes will also be summarized. Lastly, the conclusion and future scope of MXene to be done in various supercapacitor applications are also presented.

1. Introduction
The risk of energy crisis for the new generation depends on our production, storage, and utilization of the currently available fuels to produce energy [1]. Moreover, the continuous growth in the population increasing day by day and thus the energy crisis is again becoming a major concern. In this era, life without mobile phones, laptops, cameras, etc is incomprehensible thus leading to high energy consumption. Continuous depletion of energy resources demands a suitable, energy-efficient and environment-friendly energy storage device. Currently, a variety of energy storage devices are available e.g. batteries [2], capacitors [3] and supercapacitors [4] to overcome the above problems. But the outcomes of all these devices depend on efficiency, cost, and stability of the electrode materials that are being used in these devices. Though a large number of noble metals e.g. Pt, Ru, Ir as an electrode has been used for storing the energy to fulfill the energy requirements due to limitations such as high cost and less availability of these metals reduces their use in practical day to day needs [5–11]. Hence, a number of noble non-metals [12–15] are presented but their performance is poor as compared to the noble metals. Therefore, the major research area in this field is to find the efficient fabrication methods or evolution of new electrode materials that can help in achieving the future energy requirements [16]. A large number of carbon derivatives [4], metal oxides and conducting polymers are used as an supercapacitor electrodes e.g. activated carbon [17], carbon nanotubes [18], carbon aerogels [19], graphene [20], ruthenium dioxide [21], magnesium oxide [22], polypropylene, polyaniline and poly-ethyl dioxithiophene [23] etc. The activated carbon was successfully used in supercapacitor as electrode material in the year 2006 due to its large number of advantages like large specific surface area (up to 3000 m² g⁻¹), abundance, simple production method. It can be prepared from both the natural (coal, wood, coconut shell) and chemical precursor [17]. However, the capacitance results obtained whereas very limited due to the presence of various pore size distributions [24] as during the activation process of activated carbon, the controllability in the formation of micro, meso, and
promising electrode material in energy storage and conversion devices because of its excellent properties. The MXene belongs to the family of 2D layered transition metal carbides, nitrides or carbonitrides. It is evolved as macropores is very limited [17] because of its low-cost but used very limited in the literature due to low conductivity for other metal oxide materials. The magnesium oxide (MgO) is discovered. The major drawbacks of these 2D electrode materials include poor specific capacitance, less electrical conductivity, structure degradation and limited transport of the ions/electrons. The serious obstacle in many of these electrode materials includes expansion in the volume, less interlayer spacing, less conductivity, and hydrophobic nature. Moreover, the surface oxidation and surface defects limit their scope for energy storage applications [32]. In 2011 Naguib et al [33] showed the potential application of MXene as electrode material in supercapacitor with remarkable device performance. However, MXene [32–34], a new member of the 2D family is unique in the way that it has large interlayer spacing, excellent electrical conductivity, fast diffusion of ions and molecules, easily accessible structure, good thermal stability, hydrophilic nature, thickness controllability, and large surface area. However, the problem of restacking in MXene sheets can be easily avoided by including various spacers between the MXene layers. In viewing the above fact, the MXene seems to be the most promising candidate as an electrode material because the separation between MXene layers can be controlled systematically [35]. This aspect of the MXene is highly under research and required a comprehensive list of the work done in this area. Hence, on the MXene materials, a highly focused review is needed to be discussed for their development as emerging electrode material in energy storage applications. This review addresses the latest trend of MXene synthesis using various etchants such as hydrofluoric acid, hydrazine, lithium fluoride and hydrochloric acid. Also, the effect of intercalating cations on the MXene interlayer distance in various energy storage devices is reviewed. Finally, an outlook on future scope of MXene as an electrode material in supercapacitor related applications will be discussed.

2. Synthetic approaches for preparing 2D MXene from MAX precursor

MXene belongs to the family of 2D layered transition metal carbides, nitrides or carbonitrides. It is evolved as promising electrode material in energy storage and conversion devices because of its excellent properties. The precursor material for MXene preparation includes titanium aluminum carbide (Ti₃AlC₂) [36] which is prepared from the ‘pressure less calcination’ of titanium, aluminum, graphite. The raw material such as Ti (<40 μm powder size, 99% purity), Al (<40 μm powder size, 99% purity) and graphite powders (<5 μm powder size, 99% purity) can be taken as a starting material in the proportion of 3:1:2 and mixed in ethanol solution under 20MPa pressure. The single-phase precursor can be obtained after calcining at 1400 °C for 4 h.

The reactions that occurred during the formation of ternary carbide are shown above. The ternary carbide shows both the combinative properties of ceramics and metals. It resembles the metals in the way that it is thermally and electrically conductive, shock resistance. Like ceramics, it is lightweight, stiff, thermally stable and retained its properties even at high temperatures. Hence, it is considered as an attractive material for various applications. The ternary carbide is synthesized by various researchers by various techniques [37–39]. But all these techniques include various intermediate quite stable binary and ternary phases like TiC, Al₃Ti, Al₂Ti, AlTi, etc [36].

Earlier people were used gaseous halides in vacuum to etch the A atomic layer from MAX precursor [40–42] while using these gaseous halides there are some serious limitations that it produced different structures (i.e. 3D in spite of 2D) of carbon and carbides because of etching of both ‘M’ and ‘A’ elements from the MAX precursor. Hence, the preparation of MXene is carried out from the formula Mₓ₋₁Aₓ₁(MAX), where ‘M’ belongs to the family of early transition metals such as scandium (Sc), titanium (Ti), vanadium (V), chromium (Cr), etc ‘A’ is an element belonging to the 12–16 group elements such as cadmium (Cd), aluminum (Al), silicon (Si), phosphorus (P), etc and ‘X’ can be carbon, nitrogen, carbon, and nitrogen [43–46]. The MXene also known as sheets of transition metal with exposed surface is prepared by removing ‘A’ elements selectively from MAX precursor using HF or NH₄HF₂ as shown in equations (1) and (4) Though the bond between M and A is metallic and strong but it is replaced by hydrogen bonds which are weaker such as hydroxyl OH, oxygen O, and fluoride F due to various etchants such as HF (aq.), NH₄HF₂ at room temperature [32, 33, 45, 47]. Since, the hydrophilicity of...
metal present in $\text{M}_{n+1}X_n$ results in the functionalization of MXene with various species such as (O, OH, F) as depicted in equations (2), (3) and (5).

$$
\text{M}_{n+1}X_n + 3\text{HF} = \text{A}E_3 + 3/2\text{H}_2 + \text{M}_{n+1}X_n
$$

(1)

$$
\text{M}_{n+1}X_n + 2\text{H}_2\text{O} = \text{M}_{n+1}X_n(\text{OH})_2 + \text{H}_2
$$

(2)

$$
\text{M}_{n+1}X_n + 2\text{HF} = \text{M}_{n+1}X_n\text{F}_2 + \text{H}_2
$$

(3)

Illustration for MXene structure is depicted in figure 1.

These functional groups greatly affect the physio-chemical properties of the final resulted product (MXene). Hence, exfoliation and etching leads to the termination of MXene with OH, O, and F groups and thus, transit the behavior of MXene from metallic to semiconducting [45]. However, in the case of etching with HF, one more step of delamination is necessary since the etching and exfoliation do not occur simultaneously. Since HF is a very strong acid there is another route reported in the literature [45] of preparing MXene from in situ HF such as LiF, NaF, and KF which are used with hydrochloric acid (HCl). This method starts by adding MAX powder in fluoride salt along with HCl solution at room temperature for a few hours, which results in a clay-like product after several washing cycles [45]. Further, the clay-like product can be transformed into different morphologies by post-processing. However, the reaction of fluoride salts with HCl results in HF, shows that fluoride formation is necessary for the production of MXene. During the reaction of HCl with the fluoride salts, intercalating the metal cations (e.g., Li$^+$, Na$^+$, and K$^+$), increases the interlayer spacing between the MXene layers. Such intercalation cannot be possible if HF is used directly. There are several factors that can affect the etching process are MAX structure, bonding between the atoms, and size of the particle, etc. Moreover, etchants other than HF if used such as (e.g. LiF, HCl and NH$_4$HF$_2$) [48] took a long time for complete exfoliation. This is due to the fact that the in situ intercalation of NH$_3^+$ and NH$_4^+$ species between MXene layers leads to the delamination of the bundles of MXene sheets into individual multilayer sheets. Hence, in this case, no additional step for delamination is required since etching occurred parallelly. Delamination and etching are the two main factors that affect the properties of the MXene flakes [49] such as flake quality, crystallinity, defects, thickness, and functionalization of the surface. Usually, smaller/multi-layered MXene flakes can be prepared by delaminating with sonication and the lower concentration of LiF, whereas large mono-layered MXene flakes can be prepared using more concentration of LiF since the use of higher concentration LiF leads to both exfoliation and etching as shown in figure 2 [50].

Hence, multilayer MXene flakes can be separated into mono/few-layer flakes even without sonication. Presently, the most promising methods of delamination in terms of efficiency include organic intercalating molecules such as DMSO and isopropyl alcohol [51]. In 2011, the first multilayer MXene is synthesized by etching A layer selectively [52]. Thereafter in 2012, new members of the MXene family appeared e.g. Ti$_2$CT$_x$ (Ti, Nb)$_2$CT$_x$ [53] and (V, Cr)$_2$C$_2$T$_x$ [54]. Then, later on, delaminated single-layer MXene, small flake, double M MXene and ordered divacancies (Mo$_{0.5}$CT$_x$) have evolved. According to the literature, for synthesizing MXenes, Ti$_3$C$_2$T$_x$ was considered as a pillar for further investigations (termed as Ti$_3$C$_2$T$_x$). To date, MXene family [34] includes Ti$_3$C$_2$, Ti$_2$C, V$_2$C, Cr$_3$C$_2$, Fe$_2$C, Nb$_3$C, Nb$_2$C, Mo$_{0.33}$C, Mo$_2$C, Hf$_3$C$_2$, (V$_2$C, Cr$_2$C, and Ta$_2$C), Cr$_2$N,
Ti$_4$N$_3$, etc. has been synthesised. If special attention will be given to the materials, variety of new MXene are expected to be discovered in the future.

3. Application of MXene in batteries

Lithium-ion batteries (LIBs) are considered to be a promising candidate in the area of electrical vehicles. Graphite is used mostly as anode material in the LIBs because of its excellent properties such as cost-effectiveness, good stability, and high electronic conductivity. However, the intercalation of lithium-ion resulted in the specific capacity of battery limited to only 372 mAh g$^{-1}$ while graphite as anode [51]. Naguib et al were the first to publish the possibility for the MXenes usage in LIBs as anode [33]. This newly discovered material shows an increase in the surface area by approximately 10-fold as compared to graphene or MAX (Ti$_2$AlC). Also, it shows that there was an increase in the specific capacity to 225 mAh g$^{-1}$, which was five times greater than the MAX phase because of the greater surface area, open structure, and weak bonds between various MXene layer elements in the Ti$_2$C structure. Also, the Li$^+$ ions occupy the interlayer spacing between the sheets of Ti$_2$C. Thus, the available [55] current state-of-the-art anode materials had a better performance than graphene which leads to an idea of exploring new MXene based electrode materials. Afterward, niobium and vanadium carbides were developed as an electrode material for lithium-ion batteries by Naguib et al by removing the Al layer selectively from Nb$_2$AlC and V$_2$AlC compounds. The reversible capacity of 170 and 260 mAh g$^{-1}$ as shown by Nb$_2$CT$_x$ and V$_2$CT$_x$ at 1C, respectively [56]. As with the exfoliated graphite, similar results of layered morphology are given by new carbides as shown in figures 3(A) and (B). In addition, high cycling rates of 10 C were also withstanding by both electrode materials which shows that a fast Li diffusion can be carried out between the materials having layered structure.

Afterward, computational (DFT) studies showed the possibility of Ti$_3$C$_2$ MXene and its derivatives such as Ti$_3$C$_2$F$_2$ and Ti$_3$C$_2$(OH)$_2$ as anode materials for LIBs by Tang et al [35]. In their work, the impact of electronic properties and intercalation on bare (Ti$_3$C$_2$), fluorinated (Ti$_3$C$_2$F$_2$), and hydroxylated (Ti$_3$C$_2$(OH)$_2$) surfaces due to Li-ion was investigated. Further, the investigation of Li adsorption and Ti$_3$C$_2$ diffusion behavior was performed. Because of the low energy barrier and small path length, it was observed that it is easy for Li-ions to...
migrate on the Ti$_3$C$_2$ surface but for other derivatives of MXene such as Ti$_3$C$_2$T$_x$ (T = F or OH), a higher diffusion barrier was observed because of the retardation of the surface T groups. In the case of Ti$_3$C$_2$ derivatives, the Li-ion smooth migration was prevented by the bulky OH groups. Hence, it was concluded that the MXene material would be a reliable candidate for LIBs as anode due to its various properties such as high electrical conductivity, low diffusion barrier, and large theoretical capacity (320 mAh g$^{-1}$). Due to the intercalation and delamination of the surface-functionalized Ti$_3$C$_2$ material by hydrazine and N, N-dimethyl formaldehyde, the c lattice parameter was increased as shown in SEM image [49]. Also, the enhanced rate capability is shown due to intercalation in Li-ion batteries.

Since the intercalation process is discussed for a long time to store charge in batteries because lithium can offer a large energy density. However, to optimize electrochemical performance further, more research has to be done for understanding the mechanism of lithiumation and de-lithiation for MXene in detail. But still, it is very difficult for transportation and storage of bigger sized cations without affecting the crystal structure. Moreover, the application of LIBs is greatly reduced in energy storage and conversion applications due to the limited availability of natural deposits of lithium, its safety and production cost [57, 58] and thus leads to the generation of non-lithium-ion battery (NLB) systems such as sodium-ion, potassium-ion, Magnesium-ion, and Calcium-ion batteries, etc. [59–62]. Hence, new MX compounds were developed by Lukatskaya et al on the basis of 2D titanium carbide layered structure which was capable of accommodating a variety of cations (e.g. Na$^+$, K$^+$, NH$_4^+$, Mg$^{2+}$ and Al$^{3+}$) electrochemically from their aqueous salt solutions [63].

The main advantage of these batteries is due to their abundance, large storage capacity, wide negative redox potentials, operational safety, and environmentally friendly nature. Moreover, MXene materials have advantages such as high electrical conductivity, large surface area and tendency to accommodate a variety of cations e.g. Na$^+$ [55]. Hence, Wang et al published that in Na-ion hybrid capacitors, the Ti$_2$CT$_x$ MXene can act as an anode [64]. The intercalation/adsorption of Na ions into/onto the surface of MXene nanosheets enhances the interlayer distance between the MXene layers from 7.1 to 10.1 Å as can be seen from figure 4. Afterward, it was found by Dall Agnese et al that when V$_2$C MXene was compared with Ti$_3$C, their electrochemical behavior is similar [65, 66]. Since, till now major attention was aimed at the usage of these materials as anode electrodes. But it was presented by Dall Agnese et al that from the large family of MXenes, V$_2$CT$_x$ can also be used as a cathode electrode material [65]. The hybrid asymmetric supercapacitor was fabricated with anode as hard carbon and V$_2$CT$_x$ as a cathode. The device delivered the 50 mAh g$^{-1}$ for a 3.5 voltage window. It was depicted that the intercalation of Na-ions between the V$_2$CT$_x$ layers had the same performance as intercalating Li-ions. Hence, V$_2$CT$_x$ MXene can act as a promising positive material with a large operating voltage window. A flexible and conductive Hf$_3$C$_2$T$_x$ MXene was synthesized by Zhou et al from Hf$_2$[Al(Si)$_3$]$_x$C compound by removing Si alloyed Al–C sublayer selectively [67]. The volumetric capacities of 1567 and 504 mAh cm$^{-3}$ had been displayed by the as obtained 2D Hf-containing MXene material in lithium-ion and sodium-ion batteries for 200 mA g$^{-1}$ current density, showing that Hf-containing MXene material can be the best alternative. There is one more alternative present besides lithium-ion batteries and non-lithium ion batteries is the lithium sulphur batteries (LSBs). These batteries are considered to have a bright future in the energy storage devices because of their large theoretical capacity (1675 mAh g$^{-1}$), large availability, and greater values of specific energy density (2600 Wh kg$^{-1}$) [68, 69]. However, there are some drawbacks associated with sulfur batteries such as sulfur loss, poor cycle life, and
| Anode         | Capacitance | Application | Advantages                                                                                                                                                                                                 | References |
|--------------|-------------|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| graphite     | 372 mAh g⁻¹ | Li-ion      | Cost effectiveness, good stability, and high electronic conductivity                                                                                                                                          | [51]       |
| Ti₃C₂Tx      | 225 mAh g⁻¹ | Li-ion      | Surface area increased approximately by 10-fold and specific capacity by five times as compared to graphene or MAX (Ti₂AlC) due to greater surface area, open structure, and weak bonds between various MXene layer elements | [33]       |
| NbₓCTₓ       | 170 mAh g⁻¹ | Li-ion      | Fast Li diffusion can be carried out between the materials having a layered structure because of the high cyclic rate of 10C.                                                                                   | [56]       |
| VₓCTₓ        | 260 mAh g⁻¹ | Li-ion      | Fast Li diffusion can be carried out between the materials having a layered structure because of the high cyclic rate of 10C.                                                                                   | [56]       |
| HfₓC₂Tx      | 1567 mAh g⁻¹| Li-ion      | The good candidate as an anode material                                                                                                                                                                     | [56]       |
| HfₓC₂Tz      | 504 mAh cm⁻³ | Na-ion     | The good candidate as an anode material                                                                                                                                                                     | [67]       |
| S/Ti₂C       | 1200 mAh g⁻¹| S-ion      | MXene mono/few layers bind the soluble Li₂Sn species strongly, therefore, avoiding their dissociation into the electrolyte                                                                                      | [71]       |
| Ti₃C₂        | 320 mAh g⁻¹ | Li-ion      | Low energy barrier and small path length, let the easy migration of Li ions on the Ti₃C₂ surface but a higher diffusion barrier was observed for other derivatives of MXene such as TiₓCₓTx (T = F or OH) because of the retardation of the surface T groups. | [55]       |
| TiₓCₓTx      | 40 mAh g⁻¹  | Na-ion      | The intercalation/adsorption of Na ions into/onto the surface of MXene nanosheets enhances the interlayer distance between the MXene layers from 7.1 to 10.1 Å                                                                 | [64]       |
| VₓCTₓ (as a cathode) | 50 mAh g⁻¹  | Na-ion      | Intercalation of Na-ions between the VₓCTₓ layers had the same performance as intercalating Li-ions.                                                                                                              | [65]       |
dissolution of electrolytes. All these drawbacks prove to be the major hurdles in sulfur-based batteries, hence limits their performance. In order to tackle these problems, efficient electrode material for hosting sulfur has to be discovered. The study of titanium carbide-based MXene (Ti$_2$C$_x$CO$_2$) had been done by Zhao et al as the host material of Li$_2$Sn species for Li–S batteries by carrying the DFT computations. It had been concluded that MXene mono- or few layers bind the soluble Li$_2$Sn species strongly, therefore, avoiding their dissociation into the electrolyte [70]. Similarly, the performance of LSBs was significantly improved by Ti-based MXene (Ti$_2$C) as discovered by Rao et al using DFT calculations [71]. Due to the interaction of lithium sulfides (Li$_2$S$_n$) on the surface of functionalized MXene, their bond between Titanium and Sulphur becomes stronger that helps in preventing sulfur dissolution. Later on, it was reported that because of the strong bond between Ti-based carbides functionalized groups and the polysulfide species due to the high metallic conductivity, MXene appears as a promising candidate as hosts for the sulfur battery [71]. The S/Ti$_2$C composites with 70 wt% showed cycling performance of long-term stability and retaining capacity up to 80% after 400 cycles at 2C with a specific capacity of around 1200 mAh g$^{-1}$ current density at 5C. Table 1 summarized the capacitance and advantages of different materials used for anode and cathode electrodes for different batteries applications which have been discussed in this section.

4. Effect of interlayer distance between MXene layers in supercapacitors

2D layered electrode materials have the ability to accommodate different sized cations. This ability to accommodate the cations is known as intercalation. A variety of MXene is synthesized in the literature having structural similarities to graphene. A large number of intercalants such as DMSO, urea, hydrazine has been used for the intercalation. The most common intercalant used was hydrazine monohydrate N$_2$H$_4$H$_2$O (HM) dissolved in N, N-dimethylformamide (DMF) that has increased the interlayer spacing from 7.2 to 10.3–10.4 Å [72, 73]. To intercalate HM in fluorine terminated MXene, MXene powder is mixed in HM or HM and DMF and stirred for one day. After the treatment of MXene with the HM, the suspension is filtered, for intercalation, the washing of the sediment is done with DMF instead of ethanol [33].

Intercalation using DMSO and urea follows the same procedure [49]. MXene powder is first mixed with DMSO or urea and then the sediment is collected and dried in vacuum. For delamination, DMSO is used. After the stirring of f-Ti$_2$C$_x$ with DMSO at R.T, the colloidal suspension was centrifuged to separate the intercalated powder from the liquid DMSO. After decantation of the supernatant, deionized water was added to the residue. After bath sonication of the suspension, centrifuging was carried out and the supernatant was filtered using a porous membrane filter and dried in the oven at 70°C overnight, resulting in d-MXene ‘paper’ that detach easily from the membrane.

Using angle spinning NMP technology and DFT calculations, Satoshi Kaiyama et al illustrated the intercalation of Na-ion in Ti$_2$C$_x$T$_x$ nanosheets [74]. It had been shown that the reversible intercalation and deintercalation of Na ions were exhibited by MXene nanosheets in non-aqueous Na based electrolytes. It was also demonstrated that after the first sodiation, there was an increase in the interlayer spacing and then after sodiation, there was intercalation and deintercalation of desolvated sodium ions. However, the pillared effect of Na ions and the swollen effect caused by the penetration of solvent molecules between the MXene sheets during the complete sodiation and desodiation process, the interlayer distance was maintained. Since during the intercalation and deintercalation reactions of sodium ions, no structural change is observed since Ti$_2$C$_x$T$_x$ exhibits excellent rate capability and capacitive retention over 100 cycles. After the treatment of Ti$_2$C$_x$T$_x$ with hydrofluoric acid for 15 h at room temperature, there was a shift in the (002) peak from higher to a lower angle which showed an increase in the c-lattice parameter from 9.25 to 9.67 Å as depicted in figure 5. Then during the first sodiation process, the (002) peak further shifts to a lower angle, implying a relative expansion in the interlayer spacing from 9.7 Å (pristine) to 12.5 Å.

A publication illustrating the effect of metal intercalation on the vibrational dynamics of water molecules was presented by Naresh C. Osti et al [75]. Since the partial removal of water molecules and bonding between surface-functionalized groups and remaining water molecules leads to a reduction in the mobility of water molecules. In bare MXene, the 002 peak was found to be at 19.88 Å. After intercalation, there was a shift in the 002 peak to a lower angle, presenting an increase in the interlayer spacing. As compared to the change in the spacing between bare MXene layers, the intercalation of metal ions shows different results. After vacuum annealing, it is observed that Intercalating MXene layers with potassium ions lead to a very small decrease in the c-lattice parameter whereas intercalation with sodium ions show two peaks from which one was narrow and one was broad with 002 peak at 23.98 Å and 21.22 Å, respectively as compared to the results without annealing. Also, the results obtained with lithium intercalated MXene show the 002-peak change from 24.63 Å to 19.88 Å as illustrated in figure 6.
Effect of cation intercalation in controlling the actuation properties of MXene paper electrodes was published by Jeremy Come et al [76]. It was observed that intercalation of lithium, sodium, and magnesium lead to electrode contraction whereas there a small increase in the interlayer spacing was observed upon potassium intercalation. Following are the results obtained for the change of height with a charge to ionic radius ratios such as 1.67 Å for lithium, 1.05Å for sodium, 0.75Å for potassium and 2.78Å for magnesium [77]. Since lithium, sodium, and potassium are monovalent ions, there was a decrease in the amplitude at a large ionic radius. The effective radius of these hydrated ions is 3.82 Å for lithium, 3.58Å for sodium, 3.31 Å for potassium and 4.28Å for magnesium respectively [78]. It was observed that during intercalation, the hydration shell around the ion was completely or partially removed. As for dry MXene paper, as shown in figure 7(A), the d spacing of 10.04 Å is present corresponding to the (0002) peak at 8.83°. In figure 7(B) it was shown that during Li⁺ intercalation, there was a shifting of (0002) peak from higher to lower angles and during the deintercalation, the (0002) peak again shifts from lower to higher angle showing the contraction. Thus, it was also depicted in figure 7(C) that there is a shrinkage of the MXene layers which leads to a decrease in the interlayer spacing from 12.84 Å to 12.56 Å on Li⁺ intercalation, which approximately equals to 2.1%. Since the decrease in the d-spacing is lower than the macroscopic contraction recorded previously, additional electrostatic forces must play a role in the interactions between MXene sheets.

It was demonstrated by Meng-Qiang Zhao et al regarding the storage of magnesium ions in MXenes. The as-fabricated 3D microporous flexible and conductive MXene films were tested as a cathode in magnesium ion battery after the intercalation of magnesium ions from a magnesium-based electrolyte [79, 80]. A fabricated composite Mg₀.₂₁Ti₃C₂Tx electrode shows capacitance values of 210 mAh g⁻¹, 140 mAh g⁻¹ and 55 mAh g⁻¹ respectively at capacities of 0.5 C, 1 C, and 5 C. It was shown that after intercalating Mg²⁺ ion between the
MXene layers the (002) peak shifts from 6.5° to 5.7°. Hence, it shows that the intercalation of \( \text{Mg}^{2+} \) increases the interlayer spacing from 13.6 to 15.5 Å as shown in figure 8. A method is developed by Li et al for intercalating cations and modifying the surface for enhancing the capacitance of Ti\(_3\)C\(_2\)Tx MXenes, which was then resulted in the 200% improvement in the capacitance [81]. After the etching of aluminum layer from the Ti\(_3\)AlC\(_2\) precursor, the final MXene (Ti\(_3\)C\(_2\)Tx) material is terminated by OH and F functional groups, then treated with bases having varied cationic radii such as KOH. Due to this, the bond becomes unstable between titanium and fluorine. F terminal groups are then replaced by hydroxyl groups due to the intercalation of K\(^+\) ions between the MXene layers. Hence, due to the removal of functionalized groups such as F for MXene treated with KOH, the electrochemical performance is improved. Due to the large interlayer distance and lower fluorine concentration at the KOH-treated Ti\(_3\)C\(_2\) MXene surface, the capacitance value obtained is 517 F g\(^{-1}\) at a current density of 1 A g\(^{-1}\) because of the K\(^+\) ions intercalation. Hence, the effective route to enhance the capacitance is by combining both the mechanisms of cation intercalation and surface group modification. Because of the cation intercalation and the interlayer spacing improvement, further efforts were emphasized on bringing larger cations that can drastically modify the internal structure of the host [74, 82, 83]. There is a large possibility in the intercalation of polyatomic cations such as alkylammonium (AA) is by Ghidiu et al into MXene materials [45]. Thus, better electrolyte access can be introduced by intercalating large-sized cations into the interlayer spacing of charge storage devices. The effect of interlayer spacing for different materials on the supercapacitor device performance is summarized in table 2. Hence, by understanding the structural effects of the intercalation, experimental as well as theoretical measurements were performed to understand the best conditions for intercalating large cation. Since larger cations presence reduces the specific capacitance because a dead volume can be created in the electrode. Therefore, for some applications, larger interlayer spacing is not useful because the larger interlayer spacing between the MXene layers is not better energy storage and conversion applications.

5. Different strategies to prepare MXene films

An additive and binder-free MXene paper electrodes were prepared by filtrating delaminated MXene sheets with a thickness of 20–50nm as proposed by Mashitalir et al [49] as illustrated in figure 9. The result shows that 340 F cm\(^{-3}\) capacitance was obtained with the KOH electrolyte solution [49]. It was observed that the results
| Interlayer spacing | Material                                      | Capacitance | No. of cycles | References |
|--------------------|-----------------------------------------------|-------------|--------------|------------|
| 2.708 nm           | CTAB–Sn(IV)/Ti3C2/AC                          | 51 F g⁻¹    |              | capacity retention of 71.1% after 4000 cycles at 2 A g⁻¹ |
| 2.23 nm            | CTAB/Ti3C2                                    | 248 mAh g⁻¹ | 100 cycles   |            |
| 0.7 nm             | benzoate-α-Co(OH)₂                             | 70 F g⁻¹ at 15A g⁻¹ |            | 72% of capacitance is retained after 2000 cycles |
| 1.6 nm             | Dodecyl sulfate (DS)-α-Co(OH)₂                 | 300 F g⁻¹ at 15A g⁻¹ |              | 95% of capacitance is retained after 2000 cycles |
| 0.09 nm            | NO₃⁻-α-Co(OH)₂                                | 33F g⁻¹ at 15A g⁻¹ | 81% of capacitance is retained after 2000 cycles | |
| 8.1065 Å           | NiCo₂O₄–RGO                                   | 908 F g⁻¹   |              | 4000 cycles |
| 2.578 nm           | Clay like Ti₃C₂Tx                              | 900 F cm⁻²  | 10,000 cycles |            |
| 10 Å               | PPy/Ti3C2Tx                                   | 416 F g⁻¹ at 5 mV s⁻¹ |            | The capacitance retention was 92% after 25,000 cycles |

Table 2. Effect of interlayer distances on the electrochemical performance of supercapacitors.
obtained were better than those proposed by Naguib et al for Ti$_2$C\cite{56} due to various properties such as large surface area ($98 \text{ m}^2 \text{ g}^{-1}$), hydrophilic nature, and good conductivity. Also, the flexibility of the fabricated MXene paper may open new avenues in wearable and flexible energy storage applications. It shows that these binder-free MXene papers exhibit a specific capacity of 410 mAh g$^{-1}$ at a cyclic rate of 1C and 110 mAh g$^{-1}$ at a cycling rate of 36C. Although, due to the surface functionalities such as OH and F present on the MXene sample surfaces, the theoretical results were less as compared to measured results\cite{55}. Since to increase the value of capacitance, the key parameter is to have a greater surface area, but for multilayer MXene, the surface area is very low which is approximately $23 \text{ m}^2 \text{ g}^{-1}$\cite{52}. Hence for large capacitance results, it is very beneficial to delaminate the layers for increasing the surface area. Since the formation of mono or few-layer MXene sheets of few nm thicknesses has motivated researchers to find new avenues to fabricate various flexible energy storage devices\cite{49, 56, 63, 66}.

As reported by Ling et al flexible and highly conductive nanocomposite film was synthesized by fabricating hybrids of MXene with polymer, as shown in figure 10\cite{89}. Moreover, the hybrid film possesses a large number of advantages such as flexibility, strength, and high electrical conductivity. Among various polymers, polydiallyldimethylammonium chloride (PDDA) was used mostly for intercalating between the MXene layers because of its cationic nature, and polyvinyl alcohol (PVA), hydrophilic nature and presence of OH group in its backbone. When bare MXene and hybrid of MXene with PVA and PDDA were used as electrode materials in a supercapacitor, the results obtained for the capacitance were 300, 528, 296 F cm$^{-3}$ respectively with 2 mV s$^{-1}$ scan rate in an electrolyte solution of KOH. There was no change observed in the value of capacitance on adding the PDDA polymer because of the poor density of the composite film relative to bare MXene. However, there was an increase in the value of capacitance on mixing PVA polymer with MXene film. The reason for the enhancement in the performance of PVA as compared to PDDA is because of the improved ionic transport as well as access to MXene, along with the prevention by the PVA polymer in the restacking of MXene flakes.

Although the electrical conductivity of the composite films and the bare Ti$_3$C$_2$T$_x$ is almost identical, there were also other factors that determine the electrochemical performances of the composite film such as restacking prevention, ionic access and their transport, degree of cationic interaction, and composite film flexibility. Afterward, the clay-like MXene (Ti$_3$C$_2$T$_x$) was synthesized by Ghidiu et al using LiF and HCl solution\cite{45}. The as-synthesized MXene was rolled into thin nanosheets as shown in figure 11. When acidic electrolyte was used, additive-free Ti$_3$C$_2$T$_x$ films resulted in a volumetric capacitance of 900 F cm$^{-3}$ (or 245 F g$^{-1}$)\cite{33}. 

Figure 9. Schematic showing the fabrication of Binder and additive-free Ti$_3$C$_2$T$_x$ paper electrode.

Figure 10. Schematic illustrating the adjustable properties of MXene-based functional films. Reproduced with permission from\cite{89}.
Afterward, all MXene interdigital microsupercapacitor using spray coating method is presented by You-Yu Peng et al. The large sized MXene flakes were stacked at the bottom layer used as current collectors. The small sized MXene flakes served the top layer with various number of defects as can be seen from figure 12. As compared to the platinum current collectors, Ti3C2Tx micro-supercapacitors showed much lower contact resistance, larger capacitances and good rate-capabilities. The values for areal and volumetric capacitances are ∼27 mF cm$^{-2}$ and 357 F cm$^{-3}$, respectively, at a scan rate of 20 mV s$^{-1}$. The as fabricated devices also showed good cyclic stability and capacitance retention of 100% after 10,000 cycles [90].

A novel chemical etching strategy was developed at room temperature by Ren et al to produce porous Ti3C2T x [51]. The process first includes the usage of the transition metal salt (CuSO4, CoSO4, or FeSO4) for the catalytic oxidation of MXene flakes and then the removal of the metal oxide (TiO2), which results from the oxidation process in the oxygen-rich environment as shown in figure 13(A). It was observed that the formation of porous MXene leads to an increase in the pore volume by 10-fold containing various pores with different sizes in nm, and the specific surface area from 19.6 to 93.6 m$^2$ g$^{-1}$ as presented in figures 13(B) and (C). The results obtained showed that at 0.1C, a 1250 mAh g$^{-1}$ high capacity was obtained. Furthermore, during the removal of metal oxide, there was no serious effect observed on the surface terminated (F, O, and OH) groups by using acid etchants, suggesting that the process can be used for preparing porous structures from other MXenes. Since it was identified that the MXenes are the promising electrode material for energy storage applications, hence more effort has been aimed to improve their performance further by modifying their surface and by increasing active sites and the spacing between MXene layers. Thus, when particular functional groups are removed there is a large improvement in the electrochemical performance of MXene and an increase in the interlayer spacing. Hence, it is observed from the previous studies that the surface termination groups have a strong impact on the storage ability of MXenes e.g. the electrolyte ions transportation is hampered by fluorine and hydroxyl functional groups, thus reducing the capacity of the energy storage [91].
6. MXene based supercapacitors

First, Chang E. Ren et al. [92] studied bare MXene and its composite films using a vacuum-assisted filtration (VAF) method. 2.2 × 10⁷ S m⁻¹ and 2 × 10⁷ S m⁻¹ conductivity were obtained for composite Ti₃C₂Tx/PVA and Ti₃C₂Tx/PDDA film and 2.4 × 10⁷ S m⁻¹ for bare Ti₃C₂Tx films. It was also observed that the capacitive results of MXene were over 300 F cm⁻³ which was higher as compared to the graphene (60 ~ 100 F cm⁻³) [52], carbide-derived carbons (180 F cm⁻³) [63] or graphene gel films (≈260 F/cm³) [93] previously reported. Also, the impressive volumetric capacitance was given by PVA/MXene composite with their respective values in KOH electrolyte obtained are 528 F cm⁻³ and 306 F cm⁻³ at 2 mV s⁻¹ and 100 mV s⁻¹ as shown in figures 14(A) and (B).

Leiqiang Qin et al. reported Solution Processable Mo₁.₃₃C MXene and PEDOT: PSS and obtained a maximum capacitance of 568 F cm⁻³, 33.2 mWh cm⁻³ energy density and 19470 mW cm⁻³ power density [94]. It was observed that the capacitance and rate capability of composite Mo₁.₃₃C/MXene/PEDOT: PSS film were enhanced as compared to both pristine Mo₁.₃₃C/MXene and the nontreated Mo₁.₃₃C/PEDOT: PSS hybrids since the treatment of the composite film with H₂SO₄ increases the interlayer distance. The method for obtaining hybrid films and their fabrication in the supercapacitor is depicted in figure 15. The composite electrode treated with H₂SO₄ having a 10:1 mass ratio for 24 h possesses a volumetric capacitance to a maximum of 1310 F cm⁻³ and 452 F g⁻¹ at 2 mV s⁻¹ [95]. Before this research, only a few reports were evaluated about MXene and polymer composites as an electrode material for supercapacitor applications [88]. Later on, Sixing Xu et al. [96] reported micro supercapacitor (MSC) relies on 2D Transition Metal Carbides (MXene) thick interdigital electrodes using MEMS technology. The larger mass loading was provided by building 300 μm thick titanium carbide as interdigital fingers and polymer electrolyte (PE) as the electrodes. The results show that a specific capacitance of 276 mF cm⁻² and capacitance retention of 95% after 1000 cycles was observed. In order to stabilize the structure, PE was used instead of PTFE and PVDF since the electrode surface accessibility can be increased in PE by ions [55]. However, the increased accessibility leads to an increase in surface area and a decrease in the ionic resistance. The interspaces between layers were filled by the polymer electrolyte.
The width of electrode fingers and the separator was 300 μm and 60 μm with electrode thickness 300 μm respectively as shown in figures 16(A) and (B). The isolation between the electrode fingers was shown by SU-8 walls figure 16(C). The whole device cross-section as shown in figure 16(D). It was also observed that all the spaces of the trench were filled by composite material and due to the sinking of material, a small concave is observed in the middle during the solidification process.

Afterward, the whiskers of the nanocrystalline ε-MnO₂ were prepared by Raghavan Baby Rakhi et al. [97] on nanosheet surfaces (ε-MnO₂/Ti₂CTₓ and ε-MnO₂/Ti₃C₂Tₓ) of MXene by using direct chemical synthesis to make aqueous pseudocapacitors using nanocomposite electrodes (figure 17). Since the specific capacitance of the composite electrode was increased from 32.4 to 210.9 F g⁻¹ due to the ε-MnO₂ nanowhiskers at a scan rate of 10 mV s⁻¹ as shown in figures 18(A) and (B). Also, at the end of 10,000 cycles, the as-fabricated composite supercapacitor maintained maximum capacitance till 87.7% whereas pure MnO₂ whiskers maintain only 74.5% [52] of maximum capacitance.

Greater volumetric energy density by annealing MXene nickel oxide asymmetric supercapacitor was obtained by Qi Xun Xia et al using the hydrothermal method [98]. It exhibits 92.0 mAh cm⁻³ and 53.9 mAh cm⁻³ specific capacitance at current densities of 1 A g⁻¹ and 10 A g⁻¹ respectively with an energy...
density of $1.04 \times 10^{-2}$ W h/cm$^2$ for the power density of 0.22 W cm$^{-3}$, and 72.1% cycling stability with retention after 5000 cycles. As compared to the bare MXene, the as-fabricated TiO$_2$/C-Ti$_3$C$_2$T$_x$ MXene display lower resistivity and a bigger specific surface area, which was an important parameter in enhancing the supercapacitor performance. DMSO treatment causes the exfoliation of Ti$_3$C$_2$T$_x$ MXene obtained as depicted in figure 19(a), which shows more number of slots than before. Since the single-layered MXene has only 1nm thickness, the MXene flakes produced by using DMSO treatment results in 10–70 nm thick, hence DMSO results in many or few 10–70 layers of multilayer MXene. The FESEM image of an as-fabricated device is demonstrated in figure 19(b) which shows that there is an enhancement in the dimensions (horizontally as well

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**Figure 17.** Preparation mechanism of MnO$_2$/MXene composite. Reprinted with permission from [97]. Copyright (2016) American Chemical Society.

**Figure 18.** (A) Specific capacitances of bare MXene and ε-MnO$_2$ nanowhiskers/MXene at different current densities; (B) CV profile of ε-MnO$_2$/Ti$_3$C$_2$T$_x$ Ar composite samples at different scan rate. Reprinted with permission from [97]. Copyright (2016) American Chemical Society.

**Figure 19.** (a) as-fabricated Ti$_3$C$_2$T$_x$ MXene after DMSO treatment; (b) the as-fabricated Ni-dMXNC. [98] Reproduced by permission of The Royal Society of Chemistry.
as vertically) of the single-layered sheet because of the successful addition of the NiO nanosheets. The resistance measurements between bare MXene and Ni-dMXNC indicates the better conductivity, enhanced surface area, the active NiO covering, increase in the electrode measurements between bare MXene and Ni-dMXNC indicates the better conductivity, enhanced surface area, as vertically

neatly reduced graphene hybrid alignment of MXene sheets between the crystalline template of liquid graphene oxides and them assembled into hybrid fibers. It was shown that there was an increased in the electrical conductivity \((2.9 \times 10^9 \text{ S m}^{-1})\) and volumetric capacitance \((386.4 \text{ F cm}^{-1})\) of the as-constructed integrated fiber supercapacitor as compared to neatly reduced graphene fibers \((16.4 \text{ F cm}^{-1})\). Later on, as a promising electrode material, it was synthesized for the first time by Yangyang Wen et al \[100\] by doping nitrogen in two-dimensional MXene \((\text{N-Ti}_3\text{C}_2\text{T}_x)\) by post-etch annealing MXene in the presence of ammonia. At 200 °C, it was demonstrated that there was a remarkable increase in the c-lattice parameter by encapsulating nitrogen in the MXene structure as a heteroatom from 1.92 nm in bare MXene to 2.46 nm in N-doped MXene. Moreover, it was depicted that under ambient conditions, the MXene with doped nitrogen shows a sudden improvement in the electrochemical capacitances from 192 F g\(^{-1}\) and 82 F g\(^{-1}\) in 1 M H\(_2\)SO\(_4\) and 1 M MgSO\(_4\) respectively, which was more than those compared to bare MXene showing electrochemical capacitance of 34 F g\(^{-1}\) and 52 F g\(^{-1}\) in 1 M H\(_2\)SO\(_4\) and 1 M MgSO\(_4\).

Furthermore, it was shown in figure 20(A) that the results of cyclic voltammetry (CV) in 1 M H\(_2\)SO\(_4\) was not ideal as compared to 1 M MgSO\(_4\) electrolyte. Instead, the CV profiles in H\(_2\)SO\(_4\) electrolyte show peaks at \(-0.2 \text{ V}\) to \(-0.1 \text{ V}\) potential. It can be described that these peaks may be due to the bonding/debonding of H + ions with the terminal oxygen in the Ti\(_3\)C\(_2\)T\(_x\) electrode which further introduced the pseudocapacitance due to the change in valance state of the Ti element. Different results of gravimetric capacitance were obtained for the nitrogen-doped MXene 1 M H\(_2\)SO\(_4\) electrolyte at different temperature e.g. 34 F g\(^{-1}\) for bare Ti\(_3\)C\(_2\)T\(_x\) 192 F g\(^{-1}\) for N-Ti\(_3\)C\(_2\)T\(_x\) at 200°C, 45 F g\(^{-1}\) for N-Ti\(_3\)C\(_2\)T\(_x\) at 200°C, 20 F g\(^{-1}\) for N-Ti\(_3\)C\(_2\)T\(_x\) at 700°C at 10 F g\(^{-1}\) for N-Ti\(_3\)C\(_2\)T\(_x\) at 700°C as shown in figure 20(B). It is observed that the results of specific capacitance for some of the MXene based electrodes were less as compared with bare MXene electrodes due to the small fraction of TiC phase impurity present in the Ti\(_3\)C\(_2\)T\(_x\) for different synthesis conditions. However, these results demonstrate a remarkable improvement of 460% in the specific capacitance at 200 °C and 300 °C because of the N-doping by ammonia treatment than at 300 °C and 700 °C because of the pseudocapacitive contributions by the N-containing functionalized groups and interlayer distance improvement. At varied scan rates from 1 mV s\(^{-1}\) to 50 mV s\(^{-1}\), it was observed that rectangular-shaped CV is obtained in 1 M MgSO\(_4\) (figure 20(C)). It was shown that the maximum gravimetric capacitance reaches 52 F g\(^{-1}\) at 1 mV s\(^{-1}\) for the MXene electrodes, which was then decreased to a lower value at higher scan rates as shown in figure 20(D). As compared to the H\(_2\)SO\(_4\) (0.26 S cm\(^{-1}\)) \[101\], the conductivity of MgSO\(_4\) (0.051 S cm\(^{-1}\)) \[63\] is less and so is the capacitance.

Na Zhang et al decorated 2D Titanium Carbide with Ag-Nanoparticles \[102\]. The composite device possesses a specific surface area of 107 m\(^2\) g\(^{-1}\), 332.2 mF cm\(^{-2}\) areal capacitance at a scan rate of 2 mV s\(^{-1}\), 63.2% of the capacitance retention till 100 mV s\(^{-1}\), cycling stability with 87% of capacitance retention at more than 10,000 cycles. The

Figure 20. (A) current voltage profiles at 1 mV s\(^{-1}\) scan rate; (B) specific capacitances versus scan rate of Ti\(_3\)C\(_2\)T\(_x\) and N-Ti\(_3\)C\(_2\)T\(_x\) in 1M H\(_2\)SO\(_4\); (C) capacitance versus potential graph at a scan rate of 1 mV s\(^{-1}\); (D) specific capacitances versus scan Ti\(_3\)C\(_2\)T\(_x\) and N-Ti\(_3\)C\(_2\)T\(_x\) in 1 M MgSO\(_4\) electrolyte. Reprinted from \[100\], Copyright (2017), with permission from Elsevier.
The composite device also delivers energy density to a maximum of 121.4 μWh cm\(^{-2}\) and a power density of 17395 μW cm\(^{-2}\).

The preparation of Ag NPs/MXene was shown in Figure 21(A). The digital photographs of Ag nanoparticles, MXene nanosheets, and their mixture dispersion were shown in Figure 21(B) respectively. During colloidal dispersion, a sideline beam was incident and a strong Tyndall scattering effect was observed. In general, due to the strong bonding between the Ag nanoparticles, there was a difficulty in their dispersion. Additionally, due to its flexible nature, it can be easily wrapped over the glass tube without any change in its structure, as depicted in Figure 21(C). As it acts only as a conductive spacer in hybrid with the MXene, it does not show any contribution in capacitance. Hence, when a large amount of Ag nanoparticles is mixed, it reduces the flexibility of the hybrid paper. Table 3 shows the comparison of electrochemical performance of different 2D materials which have been used in supercapacitor.

### Table 3. Comparison of electrochemical performance of different 2D materials.

| Materials      | Capacitance     | Cycles           | References |
|----------------|-----------------|------------------|------------|
| Ti\(_3\)C\(_2\)x | 900 F cm\(^{-2}\) at 2 mV s\(^{-1}\) | 10,000 cycles    | [45]       |
| Fe\(_3\)S\(_2\) | 4200 mA h g\(^{-1}\) at 4 A g\(^{-1}\) | 20,000 cycles    | [103]      |
| Ti\(_2\)C\(_x\) | 175 mAh g\(^{-1}\) at 20 mA g\(^{-1}\) | 50–100 cycles    | [64]       |
| RGO film       | 143 mAh g\(^{-1}\) at 0.05 A g\(^{-1}\) | 50,000 cycles    | [104]      |
| Mo\(_2\)S\(_2\) nanosheets | 235 F g\(^{-1}\) at 5 mV s\(^{-1}\) | 5000 charge/discharge cycles at 1 A g\(^{-1}\) | [105] |
| VN/CNT         | 715 mF cm\(^{-2}\) at 1 mA cm\(^{-2}\) | 5000 cycles at 90° bent. | [106] |

The high demands of electrochemical energy storage devices are acquired by devoting attention to the development of advanced electrode materials. In the past few decades, drawbacks of various electrode materials such as carbon and its derivatives, metal oxides and conducting polymers discovered the interest in the exploration of new electrode materials. Since the benefits of individual layers in 2D materials have led to the discovery of new 2D materials. From this aspect, a new 2D electrode material MXene is investigated in 2011. Moreover, MXene shows excellent electrochemical properties such as brittleness, high melting point, oxidation resistant, strong electrical and thermal conductivity, hydrophilic nature, compositional variability, large surface area, and tendency to host a large variety of intercalants. Hence, it has been developed as an alternative to the previous electrode materials. In this review paper, recent technologies towards the synthesis of 2D MXene and their utilization as electrode material in energy storage devices have been illustrated. In general, the process of preparing MXene involves selective etchings Al layer from the MAX phase using HF, followed by separating the multilayer MXene into a few layers by sonication. Besides HF, other etchant mixtures that are less toxic such as LiF and HCl than HF are used to successfully etch A layer from MAX phase. Multilayered MXenes with hydrophilic surface thus can be yielded into different morphologies with different functional groups e.g. hydroxyl, oxygen, and fluorine. However, new approaches are needed to be investigated for the preparation of...
fluoride-free MXenes. Since, the advantage of large interlayer spacing between MXene layers, different sized cations are intercalated into the MXene surface proving MXene as the best candidate for the energy storage device as an electrode material. Using MXene in the LIB batteries have led to high capacity and stability. In spite of using lithium, there are a variety of cations available e.g. sodium, potassium, magnesium, etc that are intercalated between the MXene layers showing them as the best candidate for hybrid devices. Furthermore, the intercalation of larger sized cations has not fully explored because there can be a tendency that large interlayer cations lead to low conductivity. Thus, affecting the charge transfer and easy diffusion of the electrolyte ions. Also, the other composites of MXenes with the conducting polymers are yet needed to be explored. These hybrid characterizations thus contribute towards the applications of MXene in the future. Furthermore, the conductive interlayer spacers added to the MXene layers can also provide an additional route for electron-conduction by keeping suitable interlayer separations. Hence, contributing to the improvement of electrochemical performance. Hence, MXene, a new 2D material shows a great future as electrode material in energy storage keeping suitable interlayer separations. Hence, contributing to the improvement of electrochemical interlayer spacers added to the MXene layers can also provide an additional route for electron-conduction by characterizations thus contribute towards the applications of MXene in the future. Furthermore, the conductive interlayer spacers added to the MXene layers can also provide an additional route for electron-conduction by keeping suitable interlayer separations. Hence, contributing to the improvement of electrochemical performance. Hence, MXene, a new 2D material shows a great future as electrode material in energy storage devices. Because of several advantages such as avoiding the problem of restacking, enhanced electronic conductivity and stability, and easy ion/electron transfer, these MXene-based hybrids open new research in the class of energy storage and conversion applications. Hence it is reviewed that the recent advancement in the synthesis, effect of interlayer distance in energy storage devices and MXene hybrid would lead to a useful path for further investigations towards energy storage applications.

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