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Elucidating the synergy of MXene and Metal-Organic framework composite for superior electrochemical energy storage applications

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ABSTRACT

The rapid growth of next-generation electrochemical energy storage technologies has intensified interest in advanced electrode materials that combine high conductivity, tunable porosity, and structural stability. Among emerging candidates, MXenes ($Ti_3C_2T_x$) and metal–organic frameworks (MOFs) have shown unique advantages, yet their integration remains underexplored. This review systematically analyzes the synergy between MXene and MIL-53 frameworks, with emphasis on how surface terminations, interlayer spacing, and MOF "breathing" effects govern charge storage mechanisms, cycling stability, and ion transport. It consolidates synthesis strategies, interfacial engineering approaches, and recent advances in MXene/MOF composites for supercapacitors and ion-batteries, while linking process–structure–property relationships to performance evaluation. Unresolved challenges such as oxidation stability, aggregation, and limited mechanistic insights are highlighted to guide future research. By bridging material

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chemistry with electrochemical performance, this review outlines a framework for designing MXene/MIL-53 composites that balance energy and power densities for durable, sustainable energy storage.

1. Introduction

The continuous demand for sophisticated energy storage systems has created an urgent necessity to develop materials that possess advanced and efficient electrochemical energy storage capabilities, including batteries [1], capacitors, and supercapacitors that utilize the principles of electrochemical reactions [2,3]. The demand for advanced electrochemical energy storage (EES) systems has accelerated research into electrode materials that can simultaneously deliver high energy density, rapid charge–discharge rates, and long-term cycling stability [4–6]. Conventional systems such as lithium-ion batteries and supercapacitors face inherent trade-offs, which batteries provide high capacity but suffer from limited rate performance, while supercapacitors offer fast kinetics yet relatively low energy density [7–9]. This has driven interest in two material families with complementary features: two-dimensional MXenes, known for their metallic conductivity and tunable surface chemistry, and metal–organic frameworks (MOFs), valued for their high porosity and structural flexibility [10–12]. Integrating these materials, particularly MXene/MIL-53 composites, offers a pathway to overcome current limitations by enhancing ion transport, interfacial stability, and charge storage mechanisms [13],[14]. This review critically examines synthesis strategies, structure–property relationships, and performance comparisons of MXene/MIL-53 composites, while identifying research gaps and future directions for next-generation energy storage devices.

Electrochemical energy storage systems function through the effective transformation of electrical and chemical energy via mobile ions with minimal combustion [15],[16]. These EES present numerous benefits, such as substantial energy storage capacity, improved ionic conduction, and elevated specific capacitance. Lithium-ion batteries and supercapacitors fundamentally depend on electrode materials characterized by high electroactivity, conductivity for electrons or ions, and stability in terms of structure or electrochemistry [17]. The effective operation of these electrochemical devices is contingent upon the properties and mechanisms associated with the specific electrode being examined. The mechanisms pertinent to the electrode in question have led to the identification of three primary categories of electrochemical energy storage systems: capacitive types, pseudocapacitive types, and the battery type, which functions through faradaic reactions [18–20]. Despite the advent of rechargeable batteries and similar technologies that utilize Li^+, Na^+, Mg^{2+}, and Al^{3+} as mobile ions for energy conversion [21], supercapacitors and capacitors provide high power density and a long operational lifespan across a broad spectrum of temperature applications [22].

Recent studies have illustrated the electrochemical characteristics of different MOF/MXene composites. However, there is still a lack of specific research documenting the electrochemical performance of $Ti_3C_2T_x$/MIL-53 composites. Several excellent reviews have

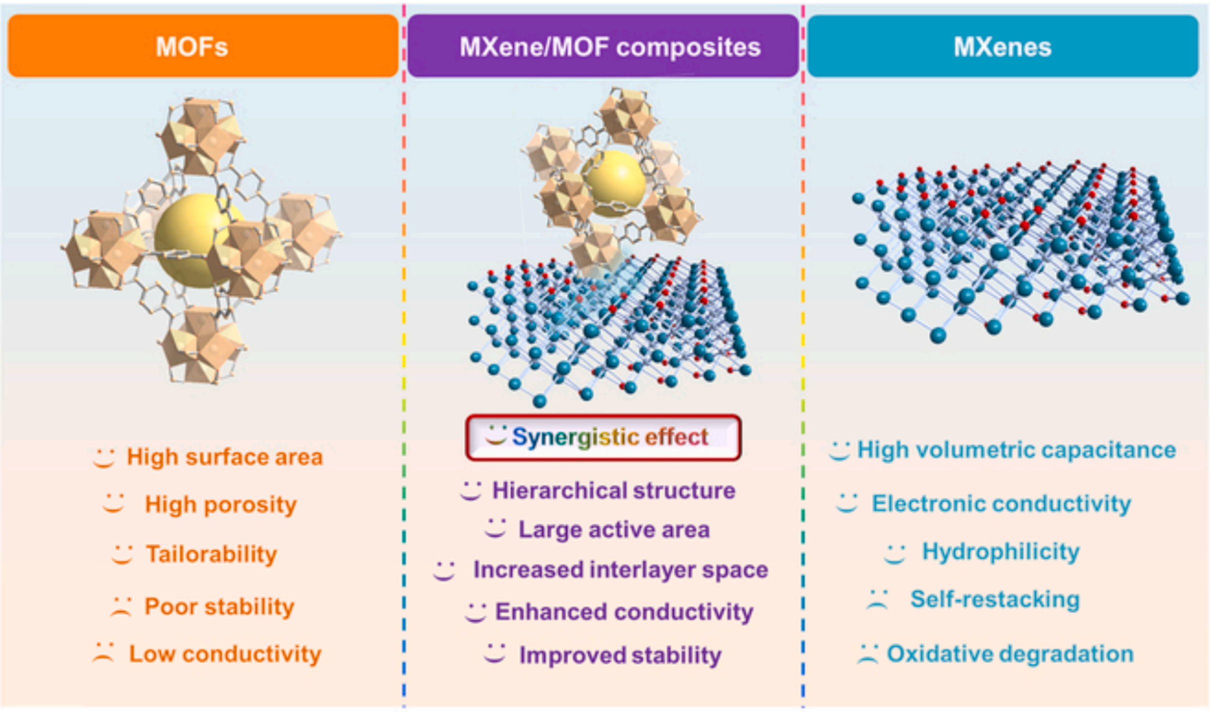


Fig. 1. Illustration of the synergistic effects of MXene/MOF composites as well as their individual properties [25].

recently summarized MXene/MOF hybrids for energy storage, including the works by Venkateswarlu et al. [23] and Ji et al. [24]. These reviews provide broad overviews of synthesis strategies and electrochemical performance, but they do not specifically focus on the MIL-53 framework or systematically link synthesis routes, surface terminations, and interfacial engineering to charge storage mechanisms and cycling stability. In contrast, the present review highlights the distinct role of MXene/MIL-53 composites, critically maps the process–structure–property relationships, and consolidates the most recent advances to identify research gaps and future directions for next-generation electrochemical energy storage devices. Fig. 1 illustrates the diverse properties of MXenes and MOFs, as well as their synergistic effects, which demonstrate robust attributes for electrochemical energy storage systems.

1.1. *Structure and properties of MXenes*

Although the properties of MXenes have been extensively reviewed in the literature, this section provides a focused summary of only those features that are most relevant to their integration with MIL-53 composites. In particular, the discussion emphasizes surface terminations, interlayer spacing, electronic conductivity, and dispersion behavior, which are the critical parameters influencing the synergistic interaction between $Ti_3C_2T_x$ MXene and MIL-53 frameworks in electrochemical energy storage applications. MXenes were first reported in 2011 by Gogotsi and colleagues at Drexel University [26]. They are two-dimensional transition-metal carbides, nitrides, or carbonitrides obtained by selectively etching the “A” element from MAX phases. Their layered structure, high metallic conductivity (up to 200,000 S/cm) [27], and tunable surface terminations (–O, –OH, –F) endow them with unique electrochemical properties [28],[29]. Hydrophilicity and large interlayer spacing promote ion diffusion, while strong M−X bonds provide structural stability. Of particular relevance to this review, surface terminations and interlayer spacing critically determine MXene’s compatibility with porous frameworks such as MIL-53, making them essential parameters for optimizing charge storage and cycling stability in hybrid composites [30–32]. Fig. 2 illustrates the different MXene phases that can be obtained through the appropriate etching procedures from the MAX phase [11].

In terms of high electrochemical performance, MWCNT/V_2CT_x hybrids have exhibited a remarkable capacitance of 1872 F/g with a capacity retention of 94 % after 1000 cycles, indicating an enhancement in reaction kinetics and outstanding conductivity [33]. The rapid charging and discharging rates, attributed to its inter-layer spacing, have significantly improved the storage capacity of electrode materials. These accomplishments stem from the inherent properties of ionic conductivity and the capacity to accommodate various customizations of the electrode in question [34]. In the realm of electrocatalysts, MXene-based materials present numerous avenues for the design and development of electrode materials [35]. Research has indicated the semiconductor characteristics of certain MXenes, which possess a band gap energy of 28.7 eV, rendering them promising candidates for co-catalytic applications [36]. The $Ti_3C_2T_x$ type represents one of the pioneering families of MXenes. This particular type is extensively studied due to its distinctive hydrophobic properties, substantial inter-layer spacing, straightforward etching process, as well as its optical and electrochemical attributes.

The $Ti_3C_2T_x$ MXene exhibits a remarkable combination of elevated electron density and significant metallic conductivity [37],[38]. It has surfaced as an exceptional material with a wide range of applications, including water splitting and the synthesis of green hydrogen [39]. Various preparation methods, such as high-temperature self-propagating synthesis, chemical vapor deposition (CVD), sintering, arc-melting, sputtering, and chemical deposition, along with solvothermal and hydrothermal techniques, have been utilized for the synthesis of MXenes since their initial discovery [40],[41]. The surface termination groups (−O, OH, and −F) provide MXenes with the capability to create hydroxyl networks within a polymeric matrix, facilitating ionic pathways that enable MXenes to engage with other materials, thereby forming MXene-based composites characterized by robust electrochemical properties [42],[43]. The layered architecture of MXene promotes ion interactions, enhancing its high surface reactivity and hydrophilicity. Notable attributes such as outstanding thermal and chemical stability, ideal crystal structure, tunable band gap energy, extensive surface area, and superior electrochemical properties and surface reactivity have positioned MXenes for a multitude of applications [44].

MXenes’ structural features are well established: XRD confirms their layered configuration and interlayer spacing, scanning electron microscopy (SEM) reveals characteristic sheet morphologies, and Fourier-transform infrared spectroscopy (FTIR) identifies surface terminations [45–47]. These properties are not just fundamental descriptors but directly govern electrochemical behavior. For instance, large interlayer spacing enhances ion diffusion, while –O and –OH groups improve wettability and interfacial bonding with MOFs [48]. In the context of MIL-53 integration, these features become decisive: hydrophilicity enables uniform MOF nucleation, metallic conductivity ensures rapid charge transport, and surface terminations regulate interfacial stability [49–51]. Thus, rather than standalone properties, MXene characteristics must be critically assessed for how they complement the porosity, flexibility, and “breathing” nature of MIL-53 to achieve enhanced energy storage performance [52]. While features such as the “accordion-like” morphology and tunable band gap values have been widely reported, their importance lies less in description and more in function [53–55]. The layered architecture facilitates ion intercalation, while surface functional groups regulate electron transfer and chemical reactivity [56]. High metallic conductivity supports rapid charge transport, and hydrophilicity promotes dispersion in solution-based synthesis routes [57]. Critically, these characteristics position MXenes as versatile partners for MOFs: their conductivity offsets the intrinsic limitations of MIL-53, while the MOF’s porosity and flexibility counteract MXene restacking and oxidation [52]. Hence, rather than viewing these attributes in isolation, it is their combined role in enabling stable, high-performance MXene/MIL-53 hybrids that defines their true value for electrochemical energy storage.

1.2. *Overview of the* $\mathbf{Ti_3C_2T_x}$ *MXene*

The $Ti_3C_2T_x$ MXene is known for its exceptional thermal and chemical stability, customizable surface chemistry, high ionic conductivity, and remarkable mechanical properties [58]. The structure of $Ti_3C_2T_x$ MXene features an alternating arrangement of

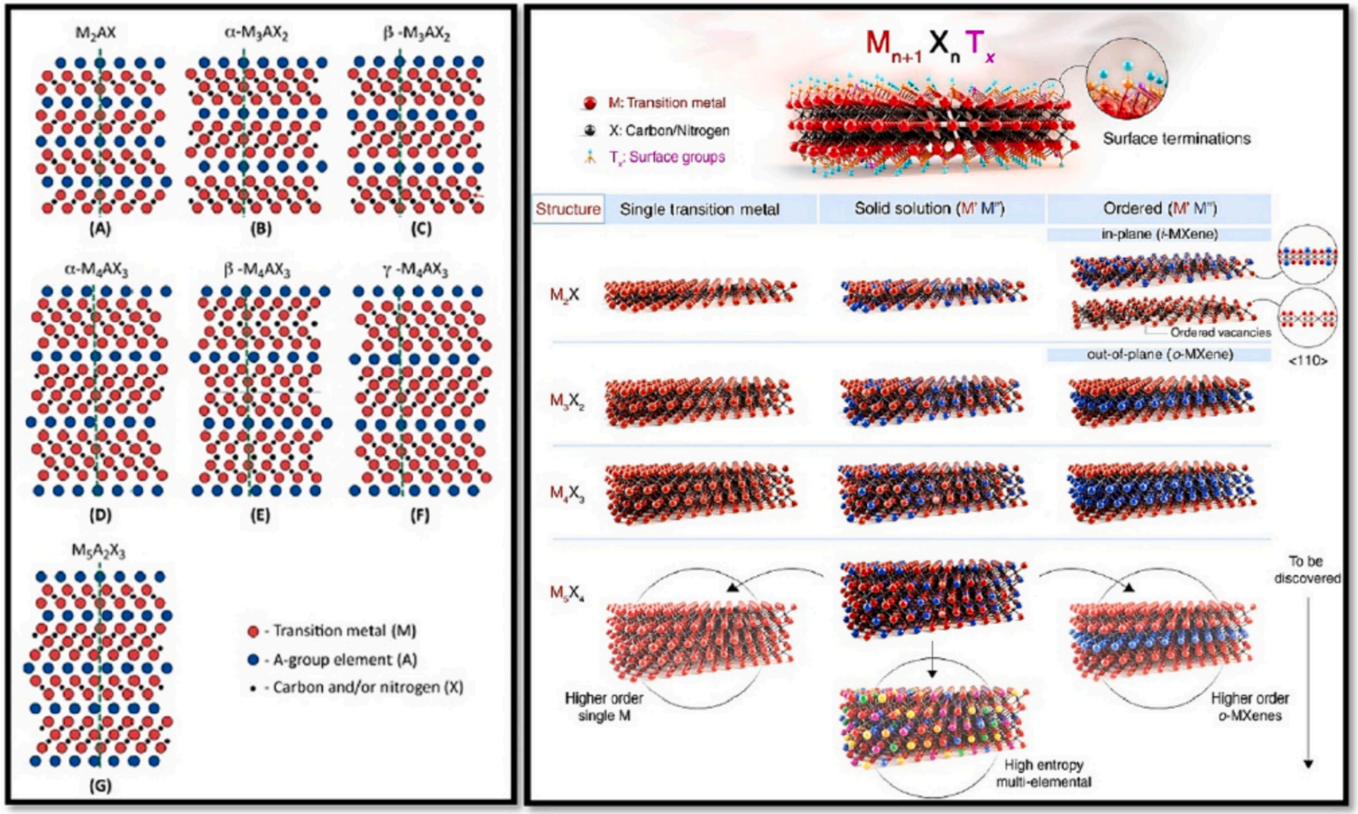


Fig. 2. Illustration of MAX phases and their associated MXenes.
Reproduced with permission from the Ref. [11].

titanium and carbon layers. Following meticulous surface exfoliation from the MAX phase, $Ti_3C_2T_x$ MXene acquires hydroxyl (OH), oxygen (O), and fluorine (F) functional groups, which are contingent upon the etching process. Typically, it is synthesized using an aqueous hydrofluoric acid solution to remove the aluminum atomic layers from the hexagonal Ti_3AlC_2. Post-etching, the T_x groups predominantly remain on the surface of the etched MXene [59],[60]. The $Ti_3C_2T_x$ MXene composite nanosheet exhibits a remarkable electrical conductivity of $4.52*10^{-4}$ S/m, a tensile strength of 66.2 MPa, and an impact strength of 24.2 24.2 Kj/m^2 with a 1.2 wt% content of $Ti_3C_2T_x$ MXene composite, as measured by the electrochemical conductivity and mechanical properties assessments conducted by Feng et al. [61]. This indicates its potential as a highly conductive filler for electrically conductive adhesives with substantial mechanical strength [62]. The well-defined porosity, extensive surface area, and numerous oxygenated functional groups of $Ti_3C_2T_x$ MXene has led to its specialized application in core–shell spheres for the ultrahigh removal of mercuric ions. The synthesized microsphere serves as a unique adsorbent for heavy metal removal from water, demonstrating an exceptional adsorption capacity of 932.84 mg for Hg^{2+} ions [63]. The chemical tunability of $Ti_3C_2T_x$ MXene enhances its functional properties, particularly as a negative electrode in sodium-ion batteries [64],[65]. The $Ti_3C_2T_x$ MXene obtained under high hydrofluoric acid concentration after thermal treatment at 300 ℃ exhibited a capacitance of 110 mAh/g at 30 mA/g as a negative electrode for sodium-ion batteries, showcasing excellent capacity retention [66]. Fig. 3 illustrates the double transition metal MXenes, which differ from their mono counterparts in that two transition metals occupy the same layer [67].

2. Synthesis of $Ti_3C_2T_x$ MXene

Although numerous reviews have already detailed the synthesis of MXenes, this section highlights only those methods most relevant to their integration with MIL-53 frameworks. The choice of synthesis route is critical because it governs surface terminations, interlayer spacing, and oxidation stability parameters that directly influence MXene's interfacial bonding and electrochemical synergy with MIL-53. In particular, etching strategies (HF, LiF/HCl, molten salt, electrochemical, and free-water) determine not only MXene quality but also its compatibility with porous MOF structures, making synthesis a decisive factor in tailoring $Ti_3C_2T_x$/MIL-53 composites for advanced energy storage [40],[68]. For example, Gogotsi and colleagues first used 50 % HF to remove aluminum from MAX phases and obtain $Ti_3C_2T_x$ MXene [69],[70]. however, this method produces F-rich surfaces that hinder electrochemical performance and raise safety concerns. More environmentally friendly alternatives, such as LiF/HCl and fluoride-free routes, generate stable MXenes with surface terminations more compatible with MOF frameworks [71]. Fig. 4 shows the general synthesis techniques for the preparation of $Ti_3C_2T_x$ MXene nanosheets.

2.1. *The LiF etching method*

Synthesis techniques such as LiF or HCl have been utilized to produce $Ti_3C_2T_x$ MXene at a temperature of 40 ℃, enhancing delamination and exfoliation while considering the reaction temperature and washing solvent [73]. The exfoliation processes are expedited by increasing the etching temperature, and at 35 °C, this can either enhance or diminish the delamination ratio. Typical

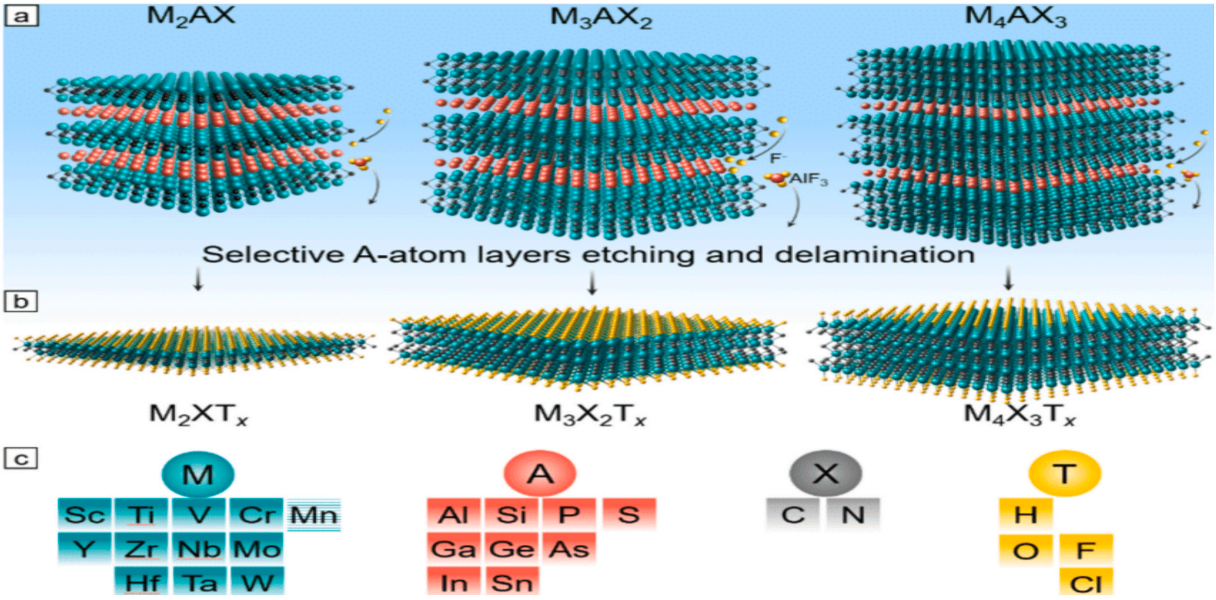


Fig. 3. Precursors of MXenes and their synthesis. (a) The selective etching of the A group layers (red atoms) and the three different mono-M MAX phases, M_2AX, M_3AX_2, and M_4AX_2. (b) Selective etching and the production of surface terminations, or yellow atoms identified as T, result in the formation of MXenes. (c) Potential components in the MAX and MXene phases for M, A, X, and T [67].

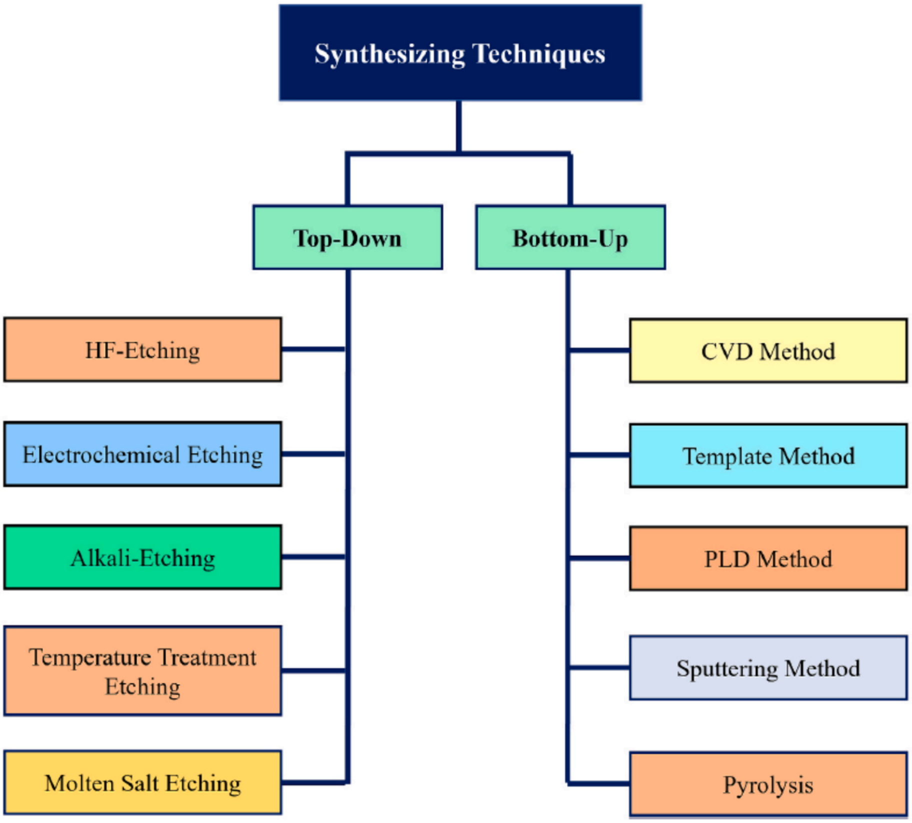


Fig. 4. General synthesis techniques for the preparation of $Ti_3C_2T_x$ MXene nanosheets. Reproduced with permission from the Ref. [72].

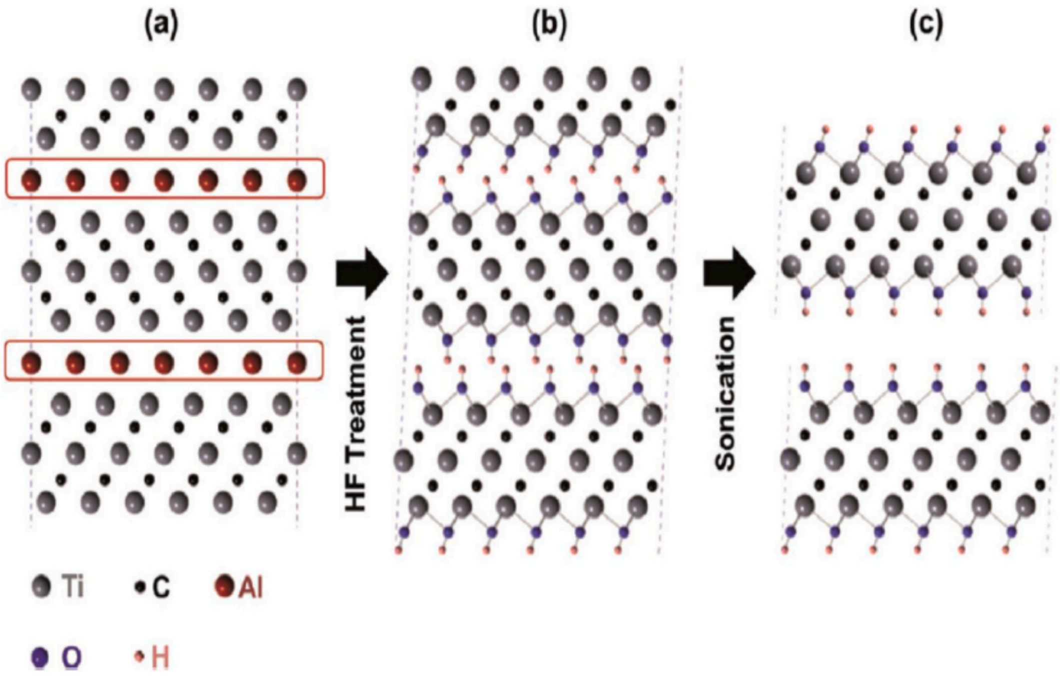


Fig. 5. A schematic representation of the Ti_3AlC_2 exfoliation process. (a) Ti_3AlC_2; (b) HF selective etching to remove Al atoms; and (c) sonication to separate $Ti_3C_2T_x$ nanosheets. Reproduced with permission from the Ref. [78].

synthesis conditions reported in the literature involve HF concentrations up to 50 % or LiF/HCl mixtures, with etching conducted at 35–40 °C for several hours, followed by repeated washing and sonication for delamination [71–73]. These parameter ranges, while variable across different studies, are highlighted here to enhance clarity and reproducibility without repeating full experimental protocols. Following one hour of basic sonication, rinsing the exfoliated product with ethanol significantly boosts the delamination ratio, reaching up to 29.2 % compared to distilled water [74]. The synthesized MXene exhibited a capacitance of 226.3 mAh/g when employed as the anode in a lithium-ion battery [75]. Abdullah et al. [76] investigated the impact of various etching agents on the synthesis of $Ti_3C_2T_x$ MXene for electrochemical energy conversion. The synthesized PtRu/MXene using the FeF_3/HCl etching method was evaluated for morphological characteristics, particle size distribution, surface chemistry, and elemental analysis through FESEM, XPS, and EIS, along with electrochemical analysis via cyclic voltammetry, revealing the highest peak density, which was measured to be 12.3 times 3.63 times greater [76]. A thorough review by Jayakumar et al. [77] also highlighted the advantages of innovative methods such as the LiF + HCl etching route over the conventional HF etching method. Fig. 5 shows a schematic representation of the Ti_3AlC_2 exfoliation process.

2.2. Molten salt etching method

An alternative approach that provides a green synthesis and environmentally sustainable technique is the molten salt method. This method has emerged as a non-toxic and non-hazardous fluoride-free technique that is both green and scalable for the synthesis of MXenes. Various Lewis acids, including AgCl, $CuCl_2$, $SnCl_2$, and $CoCl_2$, are effective in preparing uniform halogen-terminated MXenes. This technique enables the engineering of surface chemistry for MXenes, resulting in exceptional capacity and rate performance [79]. The molten salt method is favored for its versatility, which eliminates the necessity for the HF etching method while allowing for controlled surface chemistry of the resulting MXenes. It also facilitates the incorporation of functional groups that are challenging to achieve through the HF route. This approach is recognized for its customized electronic properties and enhanced chemical reactivity [80]. Liu et al. [81] successfully synthesized the exfoliation and delamination of $Ti_3C_2T_x$ MXene using the molten salt etching method. The synthesized sample underwent sonication to separate the MXene layers. The resulting MXene, utilized as a Li-ion anode, achieved a high specific capacity of 225 mAh/g at a 1 ℃ rate, along with an excellent rate capacity of 95 mAh/g at 167 ℃. These results underscore the significance of tunable chemistry in MXenes, leading to improved electrochemical performance [81]. Fig. 6 illustrates the synthesis of $Ti_3C_2Cl_2$ from the MAX phase using the molten salt method.

2.3. Electrochemical etching method

One of the recently developed etching techniques for synthesizing MXenes, which avoids the use of fluoride-based etchants, is the electrochemical etching method [83]. This technique necessitates the presence of both an electrode and an electrolyte for the reaction to take place. The aluminum layer of MAX is removed with the aid of the electrolyte through an anodic reaction, utilizing Ti_3AlC_2 as the electrode material where the etching occurs [84]. Yin et al. [85] have reported the synthesis of $Ti_3C_2T_x$ MXene with controlled fluorination via the electrochemical method for applications in lithium-ion batteries. The resulting $Ti_3C_2T_x$ MXene exhibited electrochemical activity, contributing to the remarkable cycling stability of MXene anode-based lithium-ion batteries [85]. A simplified fluoride-free synthesis of $Ti_3C_2T_x$ MXene through electrochemical etching was employed to produce a high-performance electrochemical capacitor. The resulting delaminated MXene ($Ti_3C_2T_x$) flakes measured 3.8 μm in size and 3.9 nm in thickness, demonstrating

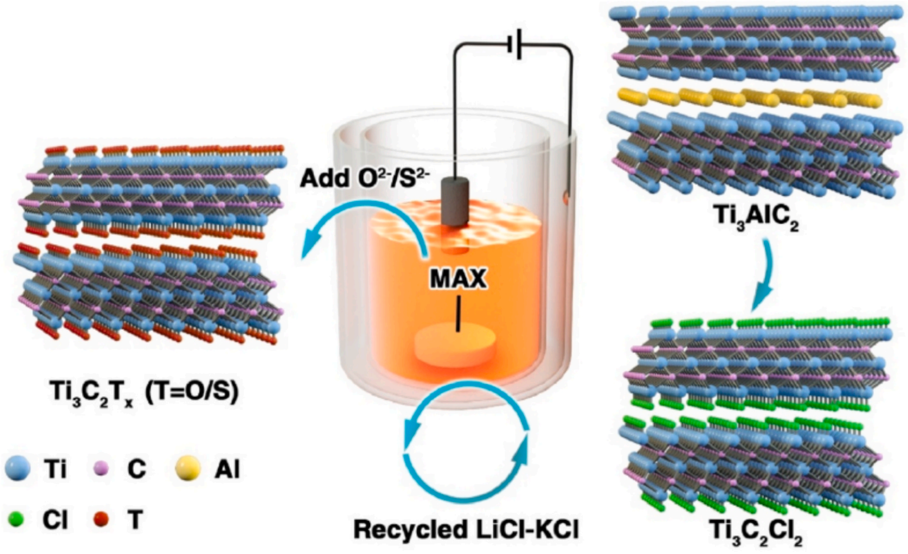


Fig. 6. Synthesis of $Ti_3C_2Cl_2$ from the MAX phase using the molten salt method. Reproduced with permission from the Ref. [82].

exceptional stability in aqueous solutions for a duration of two weeks. The filtered $Ti_3C_2T_x$ film exhibited a tensile strength of 20.5 MPa, a Young's modulus of 13.4 GPa, an electrical conductivity of 1663 S/cm, and a specific capacitance of 323.7F/g [86]. Wu et al. [87] utilized the electrochemical synthesis method to investigate the electrochemical properties of V_2 C MXene in both open and closed environments at 90 °C. The open process was conducted using an oil bath under atmospheric pressure, while the closed process was performed through hydrothermal reactions under high pressure. The samples synthesized in the closed environment demonstrated superior purity and a well-layered structure compared to those produced in the open environment, indicating enhanced electrochemical performance as an anode material for lithium-ion batteries [87]. $Ti_3C_2T_x$ MXene sheets prepared using a selective HF etchant solution exhibited a sheet-like morphology with excellent electrochemical performance, confirming the presence of titanium and carbon following EDS analysis [88].

2.4. *Free-water etching method*

Free-water etching has recently been recognized as an alternative synthesis technique for producing $Ti_3C_2T_x$ MXene, which provides exceptional stability to the resulting products. This method utilizes polar organic solvents during the etching process, capitalizing on the hydrophilic characteristics of $Ti_3C_2T_x$ MXene [89]. Natu et al. [90] documented the synthesis of two-dimensional $Ti_3C_2T_x$ MXene through the free water etching of Ti_3AlC_2 in polar solvents. The resulting MXene was extensively fluorinated, exhibiting remarkable properties, including optical, electronic, and catalytic attributes when using NH_2HF_2 in a polar solvent. In comparison to oxygen-rich terminations achieved with water as the etchant, the electrode produced demonstrated superior capacitance as an anode for sodium-ion batteries [90],[91]. The application of deep eutectic solvents (DES) at near-ambient temperatures has been shown to yield few-layered $Ti_3C_2T_x$ MXene with an optimal capacitance of 320F/g at a rate of 2 mV/s. The $Ti_3C_2T_x$ MXenes synthesized via DES displayed long-term stability, maintaining up to 97 % capacity retention over 50,000 cycles at a current density of 50 mA/g. The $Ti_3C_2T_x$ MXene synthesized in this manner features O-termination with minimal oxidation and exceptional specific capacitance, resulting in a higher inter-layer spacing compared to $Ti_3C_2T_x$ MXenes etched with water [92]. Managing the surface termination of $Ti_3C_2T_x$ MXenes significantly improves oxidation stability in sensitive applications, as the exposure of Ti-OH layers accelerates the oxidation process [93].

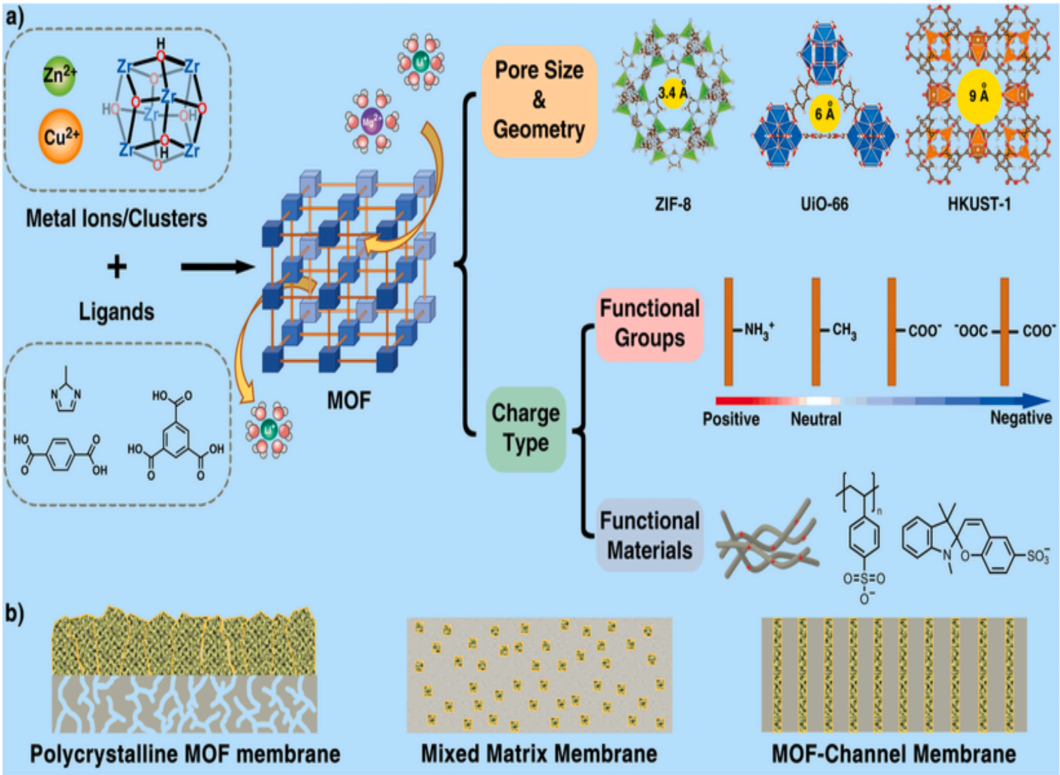


Fig. 7. Features of MOF-based membranes and metal–organic frameworks (MOFs) in terms of structure. a) MOF structure and future approaches for the separation of mono- and divalent ions (e.g., Li^+/Mg^{2+}). Metal ions or clusters arranged in relation to organic ligands make up MOFs. Changes to the pore size, shape, and charge type can enhance the ion selectivity. MOFs can have a positive or negative charge type by adding functional groups by attaching them to ligands or by packing functional molecules or polymers into framework cavities. b) MOF-channel (MOFC), mixed matrix membrane and polycrystalline MOF (PMOF) membrane structures. Reproduced with permission from the Ref. [108].

3. Overview of MOFs

Metal Organic Frameworks, in contrast, are crystalline substances composed of metal nodes interconnected by organic linkers, resulting in a substantial surface area characterized by intricate porous structures [94–96]. These frameworks are frequently utilized for gas storage owing to their extensive surface area and exceptional porosity [97]. Nevertheless, comprehensive investigations have revealed additional uses for MOFs, including liquid or gas adsorption and the development of electrodes in batteries and supercapacitors for energy storage purposes [98], thereby opening avenues for extensive research. The organic ligands present in MOFs can serve as a carbon source to create uniform structures in either two-dimensional or three-dimensional carbon frameworks, enhancing electrical conductivity for use as electrode materials [99],[100]. MOFs exhibit structural diversity with adjustable active centers when utilized in energy conversion applications. The inherent porosity of MOFs facilitates the encapsulation of various catalytic applications as active materials, which are classified based on their metal nodes. For example, metals such as Zn, Zr, Co, Cu, Fe, and Ti provide distinctive metallic nodes with varying properties [101]. Zinc-based variants like ZIF-7 and ZIF-8 are cost-effective and abundant, demonstrating promising performance as photocatalytic materials. A range of synthesis methods, including sonication, electrochemical processes, water-reflux synthesis, microwave techniques, hydrothermal reactions, oil-bath methods, solution precipitation, and solvothermal approaches, have been employed to produce various MOFs tailored to specific desired properties [102],[103].

The electrochemical performance of MOFs has been found to be contingent upon the type of architectural morphology (0D, 1D, 2D, or 3D), which primarily dictates the design and synthesis pathway employed in the preparation of the electrode material [104]. The selection of materials such as MOF-5 and Co-MOFs, along with the characteristics of organic ligands like ZIF-67 and MIL-53, significantly affect the energy storage capabilities of MOFs [105]. Among the various documented MOF variants, only a limited number exhibit a structural phenomenon known as the “breathing” feature [106]. This phenomenon corresponds to a reversible alteration in the framework conformation induced by external stimuli, leading to changes in the cell parameters. Typically, such stimuli are regulated by factors such as temperature, external pressure, or the presence of specific guest molecules that interact with the framework’s cell pores [107]. A representative series of MOFs that demonstrate this structural adaptability includes the MIL-53 MOF (which stands for Material of Institute of Lavioser). The accompanying Fig. 7 illustrates the structure, framework, ligands, and membrane formation of MOFs. This comprehensive review by Hou et al. [108] focuses on lithium extraction using emerging MOF membranes.

3.1. Properties and applications MIL-53 MOF

MIL-53 is a specific type of MOF composed of metal ions such as aluminum and chromium, along with organic linkers like

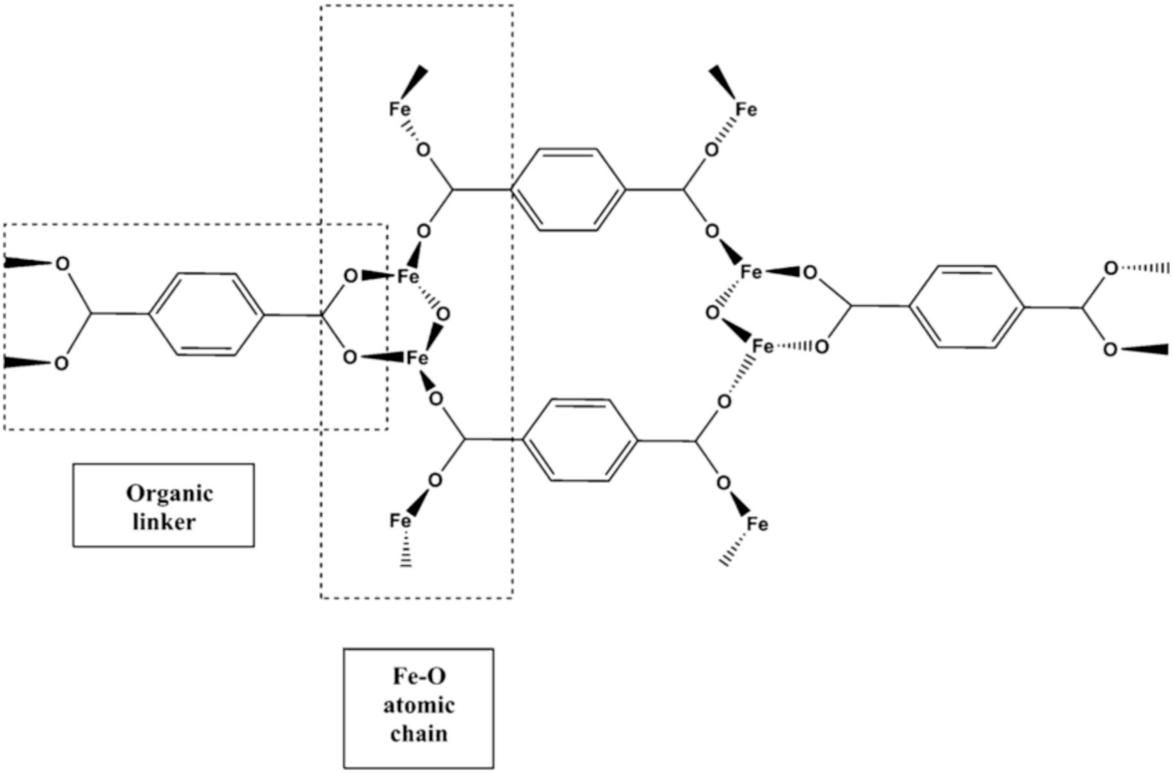


Fig. 8. Structural illustration of the Fe-based MIL-53(Fe) MOF. Reproduced with permission from the Ref. [113].

terephthalic acids. This MOF variant is highly favored by researchers due to its significant porosity, chemical tunability, and capacity for ion storage in electrochemical energy storage applications [109]. Various metal ions, including Sc^{3+}, V^{3+}, Cr^{3+}, and Al^{3+}, have been identified as contributors to the distinctive framework of MIL-53 [110]. Research has indicated that the characteristics of the linker molecules significantly influence the framework's breathing behavior. A computational investigation utilizing ideal adsorbed solution theory (IAST), along with molecular dynamics and grand-canonical Monte Carlo simulations, was conducted to reveal the structural and gas adsorption properties of MIL-53 (Cr, Fe, Al, Sc) MOF at elevated temperatures. The analysis of adsorption isotherms demonstrated the influence of temperature on gas adsorption behavior, highlighting the selective adsorption of CH_4 over CO_2, H_2S, and N_2 [111].

The material is recognized for its uses in areas such as drug delivery, gas adsorption, and separations. However, there is limited understanding of its potential application in electrochemical energy storage systems [109]. In addition to the restricted applications, there are also few synthesis routes available for the preparation of MIL-53. In comparison to other types of MOFs, MIL-53 possesses a relatively large surface area, which contributes to its outstanding performance in pollutant removal. Various factors, including the hydrothermal route utilized, the ratio of components, the type of organic solvent, and the pH value, significantly affect the synthesis process and the resulting products. At present, the most commonly used synthesis methods for the preparation of MIL-53 MOFs include the hydrothermal method, microwave-assisted method, and mechanical or ball milling method [112]. Fig. 8 illustrates the structure of the Fe-based MIL-53, which was prepared by Ghasemzadeh et al. [113] who employed MIL-53(Fe) as an effective and reusable catalyst for the synthesis of Pyrano [2,3-c] pyrazoles [113].

3.2. *Synthesis of MIL-53 MOF*

For MIL-53, hydrothermal synthesis is typically carried out at temperatures of 200–220 °C for 24–72 h using metal salts (e.g., Al^{3+}, Fe^{3+}) and terephthalic acid in aqueous or mixed solvent systems, sometimes with pH adjustment. Alternative microwave-assisted routes can reduce the synthesis time to a few minutes while maintaining crystallinity [114–116]. These parameter ranges summarize the most frequently reported conditions and provide clarity for reproducibility. The hydrothermal synthesis of MIL-53 necessitates the use of $Cr(NO_3)_3.9H_2O$, terephthalic acid (H_2 BDC), and water, typically in a ratio of 1:1:280, along with a small quantity of hydrochloric acid. This mixture is stirred continuously to ensure uniform distribution. Subsequently, it is placed in a polytetrafluoroethylene reactor and subjected to airtight heating at a constant temperature of 220 ℃ for a duration of up to 72 h [114]. After heating, the product is cooled and rinsed with deionized water to yield the MIL-53 MOF. The resulting MIL-53 predominantly features terephthalic crystals adhered to the inner surfaces of its pores, which are purified to eliminate excess terephthalic acid, thereby enhancing the surface area of the MIL-53 [115]. Due to the insolubility of terephthalic acid in water, dimethylformamide or ammonium fluoride is employed to facilitate its solubility. The hydrothermal synthesis approach is notably straightforward and environmentally benign; however, it necessitates an extended synthesis duration to achieve complete preparation of the MOFs [116]. Fig. 9 shows the synthesis of MIL-53(Fe).

3.3. *Microwave-assisted method*

To accelerate the synthesis of MIL-53, the microwave method is predominantly utilized [118]. This technique employs

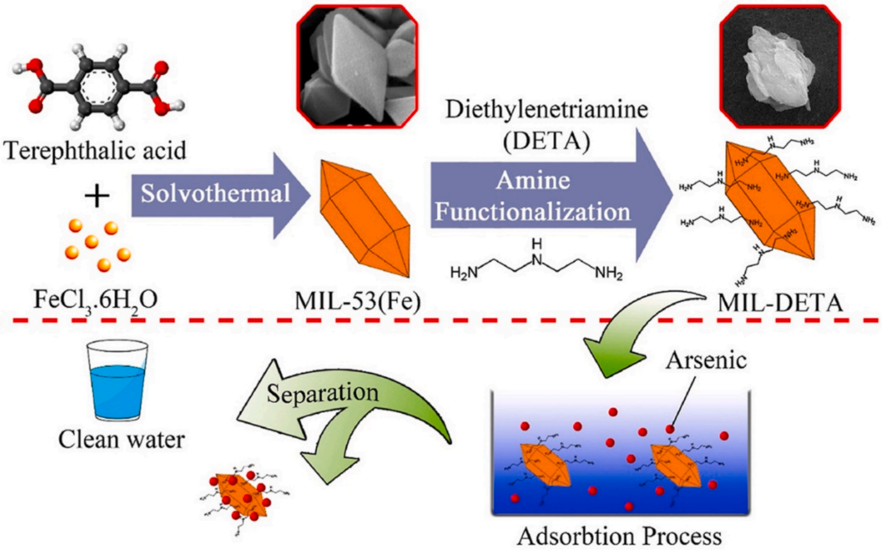


Fig. 9. Synthesis and diethylenetriamine functionalized MIL-53(Fe) Fe-based MOF for the removal of pollutants from water surface. Reproduced with permission from the Ref. [117].

electromagnetic radiation to enhance the reaction process, leading to the swift crystallization of MIL-53 [119]. Sun et al. [120] implemented a straightforward microwave-assisted solvothermal synthesis to produce aluminium-based MIL-53(Al) utilizing H_2 and N, N′ −dimethylformamide as co-solvents for CO_2 adsorption. Various parameters, including pre-mixing, microwave temperature, and reaction duration, were adjusted to assess their effects on the crystal structure, morphology, and CO_2 adsorption capacity of the synthesized MIL-53(Al). The resulting MIL-53(Al) exhibits a high surface area of 961 m^2/g, a pore volume of 0.46 cm^3/g, and thermal stability up to 480 ℃, with a CO_2 adsorption capacity of 2.16 mmol at 25 ℃, surpassing that of MIL-53(Al) synthesized via conventional solvothermal methods at 130 ℃ for 48 h [120]. Chakhtouna et al. [121] documented the synthesis of a MIL-53(Fe) biochar composite derived from date palm for the removal of ciprofloxacin and ofloxacin antibiotics using the microwave-assisted technique. The findings indicated a synergistic effect of the composite, demonstrating exceptional adsorption capacities of 218.29 mg/g and 223.89 mg/g [121]. The direct interaction between radiation and the reactants offers a superior heating method, resulting in uniform heating across the sample and enhancing the crystal size of the resultant material [122],[123]. Within a few minutes, highly crystalline MIL-53 can be effectively synthesized using the microwave-assisted approach. Numerous studies in this area have embraced this technique, particularly the straightforward microwave-assisted methods [124–126].

3.4. Mechanical or ball milling method

The mechanochemical approach, also known as the ball milling technique, has emerged as a promising method for synthesizing MIL-53 [127]. This technique effectively converts chemical energy to facilitate the synthesis of the material in question. In comparison to the hydrothermal and microwave methods, the mechanical approach yields MOFs with the desired properties of interest through the process of mechanical ball milling [128]. Nevertheless, there is a scarcity of literature addressing the application of the mechanical method in the synthesis of MOFs with specific electrochemical properties of interest. For commercial applications, the mechanical synthesis method is particularly advantageous as it can generate large quantities of MOFs, especially MIL-53 [109].

3.5. Electrochemical applications of MIL-53

The electrochemical characteristics of MIL-53 MOF are still in the early phases [129], although a significant number of research articles have been published regarding the electrochemical utilization of MOFs as electrode materials for various ion-battery applications [130],[131]. It has been established that the carboxylate group of MIL-53(Fe) offers numerous active sites with electrochemical properties. However, MIL-53 does not exhibit electrochemical properties due to the inactivity of the carboxylate group, which is influenced by the terephthalic acid ligands [132]. This inactivity is attributed to the inadequate electrical conductivity and the thickness of the electrolytic interphase layer that forms during the initial charge/discharge cycles [133]. Nevertheless, a study by Zhou et al. [134] has indicated a promising application of MIL-53(Fe) as an anode material. At a current density of 100 mA/g, a coulombic efficiency of 98.5 was recorded, with a capacity retention rate of 92.60 % post-conversion. The electrochemical transfer impedance of the material decreased from $3.32*10^{-14}cm^2/s$ to $1.10*10^{-13}cm^2/s$, thereby enhancing the mass transfer capacity. These findings highlight the distinctive electrochemical properties of MIL-53(Fe) and the potential of amorphous transition as a mechanism to improve the electrochemical performance of MIL-53(Fe) [134]. A rapid synthesis method for MIL-53(Fe) and Pd/MIL-53(Fe) composites via solvothermal techniques revealed the electrochemical properties and the role of palladium in conjunction with MOFs. The Pd/MIL-53(Fe) composite demonstrated superior electrochemical efficiency and a higher specific capacitance compared to MIL-53 (Fe). This outcome suggests the potential application of MIL-53(Fe) composites in electrochemical energy storage systems [135]. Wang et al. [136] improved the oxygen reduction activity and power generation capacity of microbial fuel cells by utilizing MIL-53(Fe) as an electrochemical catalyst through a hydrothermal synthesis method. The results indicated an enhancement in the porosity of MIL-53(Fe), which significantly boosted the electrochemical activity, yielding a cathodic output of approximately 0.37 V and power density of 397 ± 6.3 mW $/m^2$ making MIL-53(Fe) an attractive electrochemical catalyst with superior catalytic oxygen reduction property [136].

Conversely, Ojha et al. [137] developed an asymmetric supercapacitor that utilizes a chromium-based MIL-53(Cr) in conjunction with a bioderived porous carbon anode (BPC) derived from agricultural waste. A lithium-ion conductive solution was employed to examine the effect of the electrolyte on the electrochemical performance of the BPC/MIL-53(Cr) asymmetric supercapacitor, specifically using $LiClO_4$, a sodium-ion poly (4-styrenesulfonate) solution, and an ionic liquid-based solution. The $LiClO_4$@MIL-53(Cr) supercapacitor exhibited improved storage capabilities, achieving a specific capacitance of 70F/g, along with energy and power densities of 9.7 Wh/kg and 0.25 kW/kg over 10,000 cycles [137]. The significance of MOFs and their derived composites has been acknowledged as promising candidates for electrochemical energy storage (EES) systems [138]. These materials, including MIL-53 MOFs, possess notable properties that can be easily modified for various functionalizations necessary for electrochemical applications, in addition to their high porosity, facilitating electron transfer and adjustable volume changes [139]. The aluminium-based MIL-53(Al) has shown remarkable attributes for applications in electrochemical energy storage, resulting in outstanding chemical and mechanical stability [140]. Tran et al. [141] explored the electrochemical characteristics of MIL-53(Fe), a Fe-based MOF, as an innovative material for a sensitive electrochemical sensor aimed at detecting cadmium ions in aqueous solutions. Through a drop-casting technique, a glassy carbon electrode (GCE) was modified with synthetic MIL-53(Fe). The GCE/MIL-53(Fe) electrode exhibited consistent electrochemical behavior and effective immobilization of MIL-53(Fe) on the GCE surface, as evidenced by cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) analyses of the modified GCE. Furthermore, several electrochemical parameters were calculated for the MIL-53(Fe) modified GCE, including the electrochemically active surface area and the rate constant

(k^0). The results indicated that the electrochemical response signal of the working electrode could be significantly enhanced by the synthesized MIL-53(Fe) due to its high homogeneity and smaller particle size, as well as the high electrochemically active surface area [141]. The CV and EIS analysis of the MIL-53(Fe)-modified GCE are shown in Fig. 10 below.

4. MXene/MOF composites for electrochemical energy storage applications

Over the past two decades, research on MOFs and MXenes for electrochemical energy storage has experienced rapid growth, following a clear trend from foundational to specialized studies. In the early 2000 s, MOFs were mainly explored for gas storage and separation, but between 2005 and 2010, they began to attract interest in electrochemical systems, with early reports demonstrating their potential as porous electrodes [142–144]. The field shifted significantly after the discovery of MXenes in 2011, which led to an exponential rise in publications between 2012 and 2015 as researchers investigated synthesis strategies, surface terminations, and initial applications in supercapacitors and batteries [145],[146]. From 2016 to 2019, studies on both MOFs and MXenes increasingly emphasized interfacial design, charge-storage mechanisms, and balancing conductivity with porosity, setting the stage for hybrid concepts [55]. Between 2020 and 2022, the research direction evolved toward scaling and application-driven design, with MXenes studied extensively for rate capability and device performance, while MOF studies focused on stability and conductivity bottlenecks

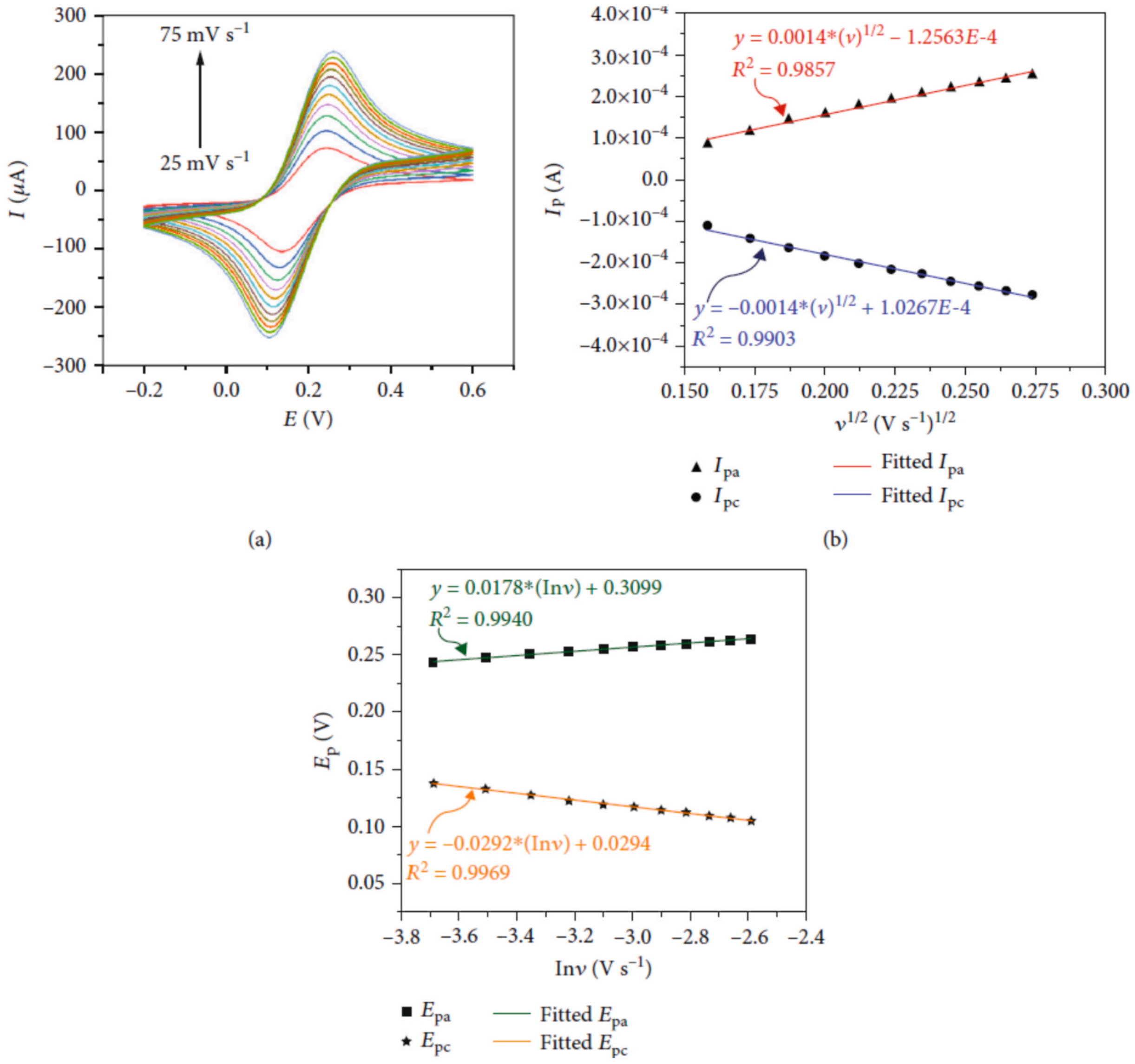


Fig. 10. A) CV analysis of MIL-53(Fe) electrode showing a scan rate between 25 and mVs^{-1}75 mVs^{-1} in 0.1 mM KCl solution containing 5 mM Fe (CN)$_6^{3-/4-}$ depicting a relation between the anodic and cathodic peaks and b) current of anodic and cathodic peaks with corresponding linear fits measuring in square root scan rates, I_{pa} (the red line with the triangle symbols) and I_{pc} (the blue line with the circle symbols) [141].

[147],[148]. In the most recent period, bibliometric analyses confirm a surge in high-impact publications, with MXene research surpassing 15,000 papers and MOFs increasingly being engineered for fast electrochemical storage [149],[150]. Within this context, MXene/MOF hybrids, though still emerging, are gaining prominence, with $Ti_3C_2T_x$/MIL-53 specifically positioned as a promising yet underexplored system that combines MXene's high conductivity with MIL-53′s breathing porosity to address limitations in ion transport and interfacial stability.

Research on MOFs (orange) shows a gradual rise from 2000, reflecting early exploration of their crystalline architectures and porosity. A sharp acceleration occurs after ∼ 2012, coinciding with the introduction of conductive MOF composites and MOF-derived carbons tailored for ion storage. MXene publications (blue) emerge after their discovery in 2011, with rapid exponential growth driven by their high conductivity, tunable surface chemistry and outstanding performance in supercapacitors and batteries. The two trajectories converge after 2018, when hybrid MOF/MXene systems gained attention for uniting porosity, redox activity and conductivity. The overall trend highlights a field-wide shift from material discovery toward engineered architectures and hybrid electrodes designed for scalable electrochemical energy storage applications. (Fig. 11).

The combination of $Ti_3C_2T_x$ MXene and MIL-53 MOF presents remarkable synergy for applications in electrochemical energy storage [13]. This synergy arises from the high metallic conductivity, mechanical strength, and exceptional surface functionality of $Ti_3C_2T_x$ MXene, which, when combined with the large surface area and high porosity of MIL-53, results in the $Ti_3C_2T_x$@MIL-53 composite [151]. These composite harnesses the strengths to produce a high-performance material characterized by superior electrochemical energy storage capacity [152]. Consequently, the objective of this section is to investigate the synergistic effects of various MXene/MOF composites, which will guide the enhancement of the performance of $Ti_3C_2T_x$ MXene, and MIL-53 composites, focusing on aspects such as energy density, high-capacity storage and retention, cyclic stability, and transfer kinetics for advanced electrochemical energy storage.

A multitude of studies have been undertaken to clarify the functional roles of these unique materials (MXene) in energy storage applications since their discovery in 2011 [153],[154]. An increasing volume of research has prompted the necessity for dependable energy storage devices that incorporate the durability of these two materials, aimed at developing high-performance electrochemical energy storage systems characterized by high power density, rapid charging, swift electron transfer, and accelerated ion movement [155]. These materials present an excellent option for the fabrication of flexible electrodes for supercapacitors, attributed to their remarkably high surface area, superior conductivity, and hydrophilicity, which results from the functional groups terminating the surface (O, F, and OH) [12]. MXene-based heterostructures have illuminated the influence of electron conductivity, interfacial interactions, ion transport pathways, and surface chemistry on the efficacy of these heterostructures in supercapacitors, batteries, and water splitting reactions [156]. A hybrid nano-architecture of $Ti_3C_2T_x$ MXene heterostructures has been utilized for supercapacitor applications. These materials ($Ti_3C_2T_x$ MXene) are recognized for their contributions to advanced electrochemical energy storage technologies. This advancement is facilitated by their highly tunable electrochemical properties, exceptional conductivity, and the abundance of active edge sites [157],[158].

Despite the various applications of MXenes in energy storage, there are challenges such as aggregation, oxidation, and restacking phenomena within the layers that hinder the full utilization of these materials in energy storage systems [159–161]. To address these challenges, Nabeela et al. [162] proposed the combination of $Ti_3C_2T_x$ MXene with MOFs, transition metal chalcogenides, and

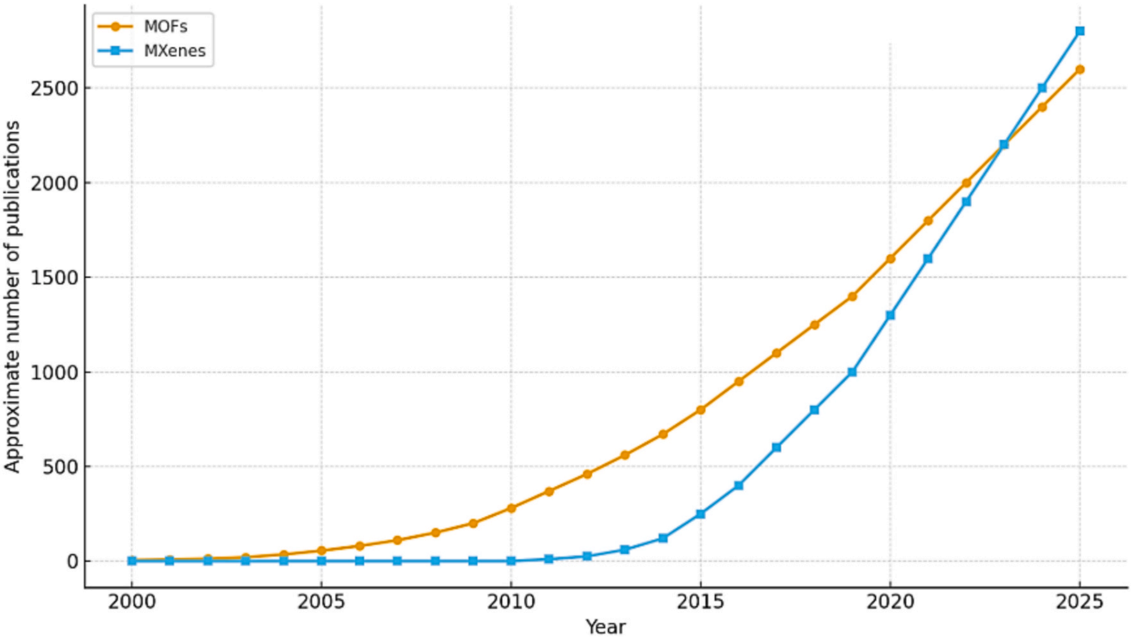


Fig. 11. Publication trends in MOFs and MXenes for electrochemical energy storage (2000–2025).

derivatives of covalent organic frameworks (COFs) as a promising composite for electrochemical energy storage applications. Investigations into heterostructures of MXene/MOFs and their derivatives have identified them as a potential electrode for batteries. In order to enhance the energy storage and efficiency of Zn-based battery electrodes, the composite material merges the high conductivity and energy density of both materials with the superior surface area and tunability of the former [163]. For example, Yang et al. [164] employed an in-situ method to construct a Sn-based MOF on MXene to promote rapid electron transport and lithium energy storage. The findings indicated that after 100 cycles, the MXene@MOF composites exhibited an outstanding reversible storage capacity of 1009 mAh/g at 0.1 A/g, showcasing excellent Li-ion storage capability. Furthermore, the research demonstrated that after 500 cycles, the MXene@MOF composite maintained impressive cycling stability and rate performance with a reversible specific capacity of 540 mAh/g [164].

Shah et al. [165] performed a comprehensive evaluation that illuminated the advancements in energy storage technologies, particularly hybrid supercapacitors. This was accomplished through the synergistic effects of MXene and MOFs composite, which has demonstrated the system's efficiency and effectiveness. The study confirmed that the integration of these two materials produces a composite with a larger surface area and abundant active sites, leading to enhanced electrochemical performance [165]. In the context of energy conversion and storage applications, various strategies have been explored to enhance MXene performance in energy storage, including surface and nano-engineering compositions with 0D, 1D, 2D, or 3D materials [166]. These dimensional materials have exhibited remarkable performance with improved properties, warranting their integration into electrochemical energy storage engineering. The combination of MOFs with $Ti_3C_2T_x$ composites has been shown to enhance efficiency in energy capture [167]. Additionally, titanium 2D and vanadium carbide MXene heterostructures have been utilized for advanced electrochemical energy applications. This combination achieved a high volumetric capacitance of 1473 Fcm^{-3} with no loss of capacitance after 50,000 charge–discharge cycles in 3 M H_2 SO_4 acid [168]. Derivatives of MOFs have displayed exquisite morphology, showcasing excellent electrochemical energy storage capacity [169]. The composite of these two materials results in improved storage capacity, accelerated ion diffusion kinetics, and increased long-term stability of the fabricated electrochemical energy storage system [170],[171].

Due to the low chemical conductivity and susceptibility to chemical instability, the integration of MOF with MXene mitigates these shortcomings by providing abundant surface terminations and remarkable metallic conductivity [25]. This enhancement improves the stability and conductivity of the pristine MOF, making it suitable for use in electrodes for supercapacitors, rechargeable batteries, and electrocatalysis energy storage systems [173]. The rationale behind the synergy of MXene/MOF hybrid designs stems from the numerous negatively charged surface groups of MOFs, which serve as effective substrates that support the growth of MOF nanoparticles and MXene sheets, thereby facilitating the exposure of a large surface area [12],[54]. Additionally, the highly conductive structure of the hybrid MXene offers extensive conductive channels and short pathways for ion diffusion [173]. The hybrid also accommodates a variety of unique designs and functionalities, owing to the strong interfacial interactions between MXene and MOFs, which provide enhanced structural integrity and stability, along with tunable crystal morphologies of MOFs [174]. This combination presents a promising outlook for high-performance electrochemical devices that are highly conductive, stable under various cycling conditions, and exhibit a high capacitance retention rate [175–177]. Furthermore, the composite necessitates a synergistic effect that provides structural support and prevents the aggregation of MXene, thereby enhancing the stability, longevity, and overall performance of electrochemical energy storage systems [178]. The high-performance Ce-Co MOFs/$Ti_3C_2T_x$ nanocomposite, synthesized via a hydrothermal method, yields a material with superior electrochemical properties. The electrochemical evaluation of Ce-Co MOFs/$Ti_3C_2T_x$ demonstrated a composite with a high capacitance of 483.3F/g at 10 mV/s and delivered a high energy density of 78.48 Wh/kg [179]. Fig. 12 shows functionalities of MXene/MOFs hybrids for electrochemical energy storage applications.

Compared to pristine MXenes, MXene/MOF hybrids consistently demonstrate improved cycling stability and higher specific capacitance, though sometimes at the expense of conductivity [12]. Among the various MOFs, ZIF-67 composites are notable for enhanced rate performance, UiO-66 composites improve thermal stability, while MIL-53 uniquely provides flexible "breathing" structures that mitigate volume expansion during cycling [181]. These contrasts highlight that future development should prioritize designing hybrids that combine MXene's conductivity with MIL-53's tunable porosity to balance high energy and power densities.

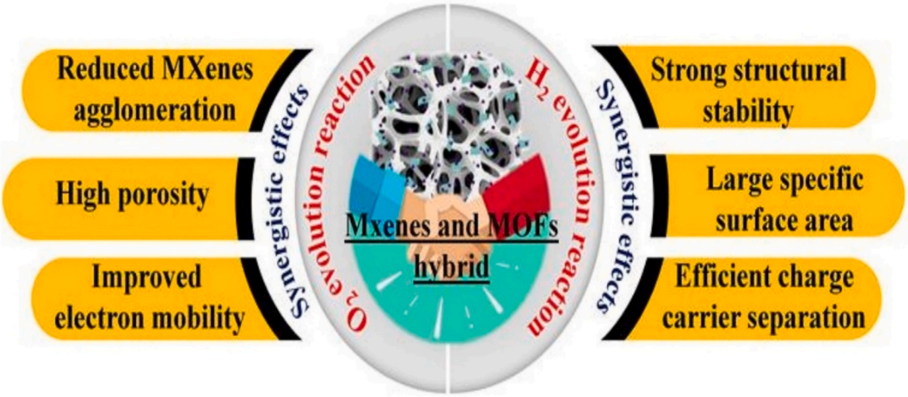


Fig. 12. Functionalities of MXene/MOFs hybrids for electrochemical energy storage applications. Reproduced with permission from the Ref. [180].

4.1. MXene/MOF supercapacitors

In the field of energy storage, supercapacitors (SCs) have emerged as crucial electrochemical energy storage devices [182]. This prominence is attributed to their remarkable energy density capabilities, rapid charge/discharge kinetics, and long-term cycling stability across numerous cycles, in addition to their exceptional storage capacities [183–185]. As research into the synergistic effects of MXene/MOF composites for enhanced energy storage devices intensifies, the design of high-performance SCs with superior energy storage capacity requires the incorporation of MXene/MOF composites as electrodes to ensure the efficient functioning of these devices [186]. The ionic conductivity of MXenes, combined with the high porosity and surface area of MOFs, results in electrodes that exhibit outstanding energy storage capacity [187]. This combination facilitates efficient charge transfer kinetics, leading to high capacitance and long-term stability. The integration of Ni-Co-MOF into MXene produces composites that demonstrate improved ion transfer, superior cycling stability, elevated energy density, enhanced conductivity, and greater capacity retention compared to pristine MXene [188]. Flexible asymmetric supercapacitors have garnered significant interest within the domain of flexible electronics. Polyaniline (PANI) and MnO_2 have generated excitement as electrode materials for flexible supercapacitors due to their high capacitance [189]. Nevertheless, the expected capacitance of these materials is short-lived due to the poor cyclic stability of PANI and the low power density of MnO_2, which restricts their applicability as storage systems [190].

Zeolites (ZIFs) derived from metal-organic frameworks (MOFs) have demonstrated potential as electrode materials for high-performance supercapacitors. Nonetheless, their low thermal conductivity, tendency to agglomerate, and insufficient stability hinder their application in electrochemical energy storage systems [191],[192]. By employing the appropriate combination, such as directly growing ZIFs on MXenes, it is possible to create high-performance supercapacitors with the requisite electrochemical properties [193].

Guo et al. [194] documented a successful hybridization of Ni-Co-ZIF/MXene composite utilizing the in-situ method to create an MXene/Ni-Co-ZDH electrode for supercapacitors (SC) that exhibited remarkable capacitance of 877F/g, exceptional stability, and a capacity retention of 90.9 % after 30,000 charge/discharge cycles, alongside an energy density of 34 Wh/kg and a power density of 748 Wh/kg [194]. Conversely, Zheng et al. [195] integrated Ni-Co_2-LDH@MXene/rGO aerogel to improve the performance stability of hybrid SCs. The resulting composites achieved an impressive specific capacitance of 332.2 mAh/g at 1 A/g with a retention rate of 87.5 % after 5,000 cycles at 5 A/g [195]. A ZnNiCo-double layered hydroxide @MXene hierarchical structure, derived from ZIF-8/67 in a 2D/2D configuration, attained a capacitance of 2011F/g at 1 A/g with a retention capability of 92.8 % after 5,000 cycles when anchored to MXene as an asymmetric SC [196].

In a separate investigation, the incorporation of α-Fe_2O_3 $-C-MoS_2$ PED:PSS into MXene resulted in an electrode with an ultra-high surface area, yielding an enhanced capacitance of 2700 mF/cm and 54F/g, along with a significant energy density of 371 μWh/cm^2, positioning it as a promising candidate for high energy density applications [197]. To address the restacking behavior of MXene-based composites, Li et al. [198] employed a freezing and thawing technique to exfoliate multilayer MXene. The resulting MXene/ZIF-8 composite exhibited a high capacitance of 1279.5F/g at 0.5 A/g, achieving a retention rate of 90.88 % after 10,000 cycles at 5 A/g. Utilizing MXene/ZIF-8 as the positive electrode in the fabricated asymmetric capacitor demonstrated outstanding electrochemical performance, with an improved specific capacitance of 354.7 Fg at 0.5 A/g and an energy density of 0.628 kWh/kg [198]. Additionally, MXene-coated carbon fibers can be developed into electrode materials for structural supercapacitors, with electrodes from this composite showcasing excellent specific capacitance of 157F/g at 5 mVs in comparison to pristine carbon fibers [199].

$Ti_3C_2T_x$ The MXene electrode, which incorporates Ni-O nanosheets synthesized through a simple and economical hydrothermal method, can achieve an impressive specific capacitance of 92 mAh/g at a current density of 1 A/g [200]. In a distinct investigation, the NiCoS4/MXene electrode exhibited remarkable electrochemical performance, attaining a specific capacitance of 1028C/g at a current density of 1 A/g and maintaining a retention rate of 94.2 % over 5000 charge/discharge cycles, functioning as the positive electrode for a high-performance hybrid pouch-type asymmetric supercapacitor [201]. This section has highlighted the importance of MXene/MOF composites as electrode materials, which improve the electrochemical performance of supercapacitors for energy storage applications. While MXene/MOF supercapacitors excel in delivering high power density and long cycle life, they are limited by relatively low energy density compared to battery systems. This contrast highlights a key development direction: enhancing pore structure and functionalizing MXene surfaces to increase energy density, while preserving the fast kinetics and durability that make supercapacitors attractive for practical applications.

4.2. MXene/MOF ion-batteries

Metal ion batteries, including Li [202], Na [203], K, Zn [204], and Al, have played a crucial role in advancing green and sustainable energy storage technologies. These batteries are classified as alkali metal-ion batteries due to their operation in an alkali medium [205],[206]. Among the aforementioned ion-batteries, the Li-ion battery is distinguished as the most reliable, trusted, and high-power density option, boasting exceptional storage capacity [207]. Nevertheless, the ongoing depletion of lithium reserves necessitates a transition to alternatives that can provide robust electrochemical performance, excellent capacity retention, and outstanding charge–discharge life cycles [208]. Numerous studies have explored MXene/MOFs composites as alternative anodic materials for LIBs and other alkali batteries [209]. Research has indicated that the performance of LIBs can be significantly improved with Co-MOF/MXene composites [210],[211]. The Co-nanoparticle contributes excellent conductivity, and when combined with the high electrochemical activity of MXene, it results in a composite with high capacity and remarkable cycling stability [212]. The MXene/Co-ZIF-67 composite has exhibited an impressive reversible capacity of 422 mAh/g after 500 charge–discharge cycles at 1 A/g, maintaining a capacity of 177 mAh/g at 5 A/g, thus presenting itself as a promising material for commercial energy storage devices [210].

The Co-MOF/V_2 CT_x MXene composite, which was synthesized using an in-situ growth method, resulted in a high-performance anode suitable for lithium-ion batteries. This composite demonstrated enhanced electrochemical stability and high conductivity, achieving a specific capacitance of 484.3 mAh/g after 120 charge–discharge cycles at a rate of 100 mAh/g, along with exceptional cycling stability at 500 mAh/h [213]. The cobalt/MXene (Co_3 O_4/Ti_3 C_2 T_x) composite, created through an ultrasonic synthesis method, serves as an electrode for high-capacity lithium-ion batteries and showcases remarkable performance, with an impressive capacitance of 999.3 mAh/g after 900 cycles and a current density of 500 mAh/g [214]. Furthermore, a three-dimensional (3D) MOF/MXene aerogel composite, incorporating hollow carbon-confined CoS nanoparticles, was developed for alkali-ion batteries via an in-situ synthesis technique. The CosNP@NH@MXene composite exhibited outstanding electrochemical performance as an electrode for lithium-ion batteries (LIBs), sodium-ion batteries (SIBs), and potassium-ion batteries (PIBs), demonstrating excellent cycle stability and high capacitance values of 1145.9 mAh/g at 1 A/g after 800 cycles, 574 mAh/g at 5 A/g after 1000 cycles for LIBs, 420 mAh/g at 2 A/g after 650 cycles for SIBs, and 210 mAh/g at 2 A/g after 500 cycles for PIBs [215].

Chen et al. [216] developed a sandwich-like composite of MOF-derived CoPNC@MXene through in-situ intercalation to improve the storage capacities of sodium and lithium-ion batteries. The resulting composite demonstrated remarkable electrochemical performance, achieving a capacity of 245 mAh/g at a current density of 100 mA/g for lithium-ion batteries (LIBs) and 101.6 mAh/g at 500 A/g after 500 cycles for SIBs. The Co-NiS@MXene composite exhibited a high specific capacity of 1120 mAh/g at 0.1 A/g after 200 cycles, showcasing excellent cycling stability and enhanced kinetics for superior lithium and sodium storage [216]. Furthermore, lithium-selenium batteries have emerged as a viable alternative to lithium-sulfur ion batteries due to their improved electrical conductivity and adjustable volume capacity [217]. The Se@Fe.CNT/TiO_2 composite, enhanced with MXene and MOF, displayed outstanding battery performance, achieving a capacity of 297.5 mAh/g after 450 charge–discharge cycles at a charging rate of 10C and a discharge rate of 1C. The synergy between the MXene/MOF composite facilitated this performance, highlighting the potential for durable and high-performance lithium-selenium batteries, thus paving the way for advanced electrochemical energy storage systems [23],[218],[219].

MXene/MOF heterostructures provide numerous active sites, enhancing electrochemical conductivity and offering remarkable stability for rapid aqueous zinc-ion batteries [220]. Lu et al. [221] developed a zinc-power anode utilizing 2D conductive MOF/MXene heterostructures, resulting in a highly efficient and stable zinc-organic battery. An asymmetric cell, which integrates the Zn-power with a MXene/Cu-THBQ anode, exhibited a high reversible cycling capacity [221]. A zero-dimensional (0D) bimetallic MOF derivative was synthesized on 2D MXene through an in-situ growth technique that employs electrostatic adsorption by Wang et al. [222]. This growth method aims to prevent the stacking of MXene, thereby facilitating dual catalytic sites on polysulfide for lithium-sulfur batteries with high areal capacity, demonstrating a high-rate capacity of 703 mAh/g at 4C at room temperature. The research indicates a potential pathway for the commercialization of Li-S batteries, attributed to their high efficiency and substantial storage capacity [222]. Numerous studies have highlighted the synergistic effects of these MXene/MOF composites and their derivatives as electrode materials fo LIBs, sodium-ion batteries (SIBs), potassium-ion batteries (PIBs), and zinc-ion batteries (ZIBs) [223–225]. Consequently, investigating MXene/MOF as alternative electrodes for ion-batteries could significantly enhance the electrochemical energy storage capabilities of these devices, paving the way for advanced energy storage systems with exceptional capacity retention across extensive charge–discharge cycles. In contrast to supercapacitors, MXene/MOF composites for ion batteries deliver significantly higher capacity but often suffer from reduced cycling stability and slower rate performance. This comparison underscores a central challenge: batteries provide energy density, while supercapacitors ensure durability and rapid kinetics. Bridging these trade-offs through interfacial engineering such as stabilizing MXene layers against restacking while leveraging MIL-53′s flexible porosity offers a clear pathway for developing next-generation hybrid energy storage devices.

4.3. Design and synthesis of MXene/MOF composites

Due to the scarcity of literature regarding the synergistic effects of $Ti_3C_2T_x$ MXene/MIL-53 composites, determining a specific preparation technique for this composite proves to be quite challenging. Nevertheless, various research studies have established both in-situ and ex-situ methods as reliable preparation techniques for the synthesis of MXene/MOFs composites [226–228]. For example, Wu et al. [229] documented the in-situ synthesis of $Ti_3C_2T_x$ /Ni-HHTP heterostructures intended for use as an anodic material in Li-ion batteries. This composite leverages the benefits of both MOF and MXene through in-situ growth, resulting in improved electronic conductivity and remarkable stability as an anode for LIBs. The initial discharge capacity of the composite electrode is recorded at 424.4 mA/g at a current density of 0.5 A/g, with a capacity of 390.2 mAh/g maintained after 800 cycles, corresponding to a capacity retention rate of 92 %. The $Ti_3C_2T_x$ /Ni-HHTP composite offers valuable insights into enhanced electrochemical energy storage systems [229]. Additionally, Adil et al. [230] reported the in-situ growth of a bimetallic Fe-Cu-MOF-MXene composite designed for a solid-state asymmetric supercapacitor, where the resulting Fe-Cu@MXene electrode exhibited an impressive specific capacitance of 440 mAh/g and high cyclic stability of 89 % after 10,000 alternating cycles, demonstrating excellent specific rate capacity [230]. Furthermore, Jakhar et al. [231] investigated the synthesis of reduced Graphene Oxides (rGO) using the in-situ method, templated with MIL-53(Fe) nanorods for photocatalytic degradation. This synthesis approach involved the use of Iron (III) chloride hexahydrate ($FeCl_3{\cdot}6H_2O$) and 1,4-benzenedicarboxylic acid (BDC) dissolved in 10 mL of DMF, which was stirred until the solution became clear. Subsequently, the solution was transferred into a stainless-steel reactor containing 10 mL of Teflon coating and heated for 7 h at 120 °C [231]. The precipitate was separated following the cooling process. To eliminate the unreacted components, the precipitate was washed with DMF and methanol (50 mL). Subsequently, the resulting sample was ground into a fine powder and dried overnight at 60 °C. Similarly, rGO (100 mg) and MIL-53 (Fe) were synthesized using the same methodology and conditions. Both the pristine MIL-53 (Fe) and the rGO@MIL-53(Fe) composite exhibited enhanced photodegradation efficiency of 99 % [231].

4.4. In-situ synthesis of MXene/MOFs composites

Due to its ease of use and controllability, the in-situ method is the most commonly used method for preparing MXene/MOF composites [232]. The technique primarily consists of combining MXene in a solution that already contains MOF precursors and reacting them under specific circumstances to form the desired MXene/MOFs composite [233]. Surface terminal groups of MXenes easily bond with the organic ligands of MOFs, creating a substantial nuclear site for MOF synthesis. Reaction parameters such as reactant concentration, solvents, temperature, and pressure influence the desired property of the MXene/MOF composite [234]. Liu et al. [232] employed in-situ growth of MXene/MOF composites for high-performance supercapacitors. The 3D hollow $Ti_3C_2T_x$/ZIF-67/CoV_2O_6 composites possess excellent electron and ion transport properties with high specific capacitance of 285.5F/g higher than the $Ti_3C_2T_x$ and $Ti_3C_2T_x$/ZIF-67 electrode. The prepared composite combined the properties of MXene and MOFs to enhance the stability and improved the conductivity of the electrode [232]. Gao et al. [235] also employed the in-situ method ad a universal strategy for the preparation of highly stable PBA/$Ti_3C_2T_x$ MXene towards li-ion battery. The developed universal synthesis was hosted on 2D MXene or rGO via in-situ transformation from ultrathin layered hydroxides (LDH) nanosheets. The optimized composite delivered a capacity of 42 mAh/g at 0.1 A/g with excellent cycling robustness when compared with the bare PBA, confirming the universal approach of the in-situ synthesis growth strategy which replaces MXene with graphene oxide nanosheet [235]. Fig. 13 illustrates in-situ growth technique employed by Bibi et al. [211] showing SEM and CV analysis at each preparation phase of the in-situ process on the study on the synthesis of MXene/MOFs composites for high performance capacitor.

4.5. Ex-situ synthesis of MXene/MOFs composites

Although the in-situ synthesis technique is widely applicable, the resulting MXenes often exhibit instability and are prone to oxidation during the in-situ hybridization process, which hinders the electrochemical performance of MXene@MOF composite electrodes [237]. To mitigate this problem, the ex-situ synthesis method has been proposed as a viable alternative for generating optimal MXene@MOF composites that possess enhanced electrochemical properties [238]. The fabrication of MXene/MOF composites typically involves techniques such as vacuum filtration, ultrasonication, and self-assembly, wherein pre-synthesized MOFs are directly

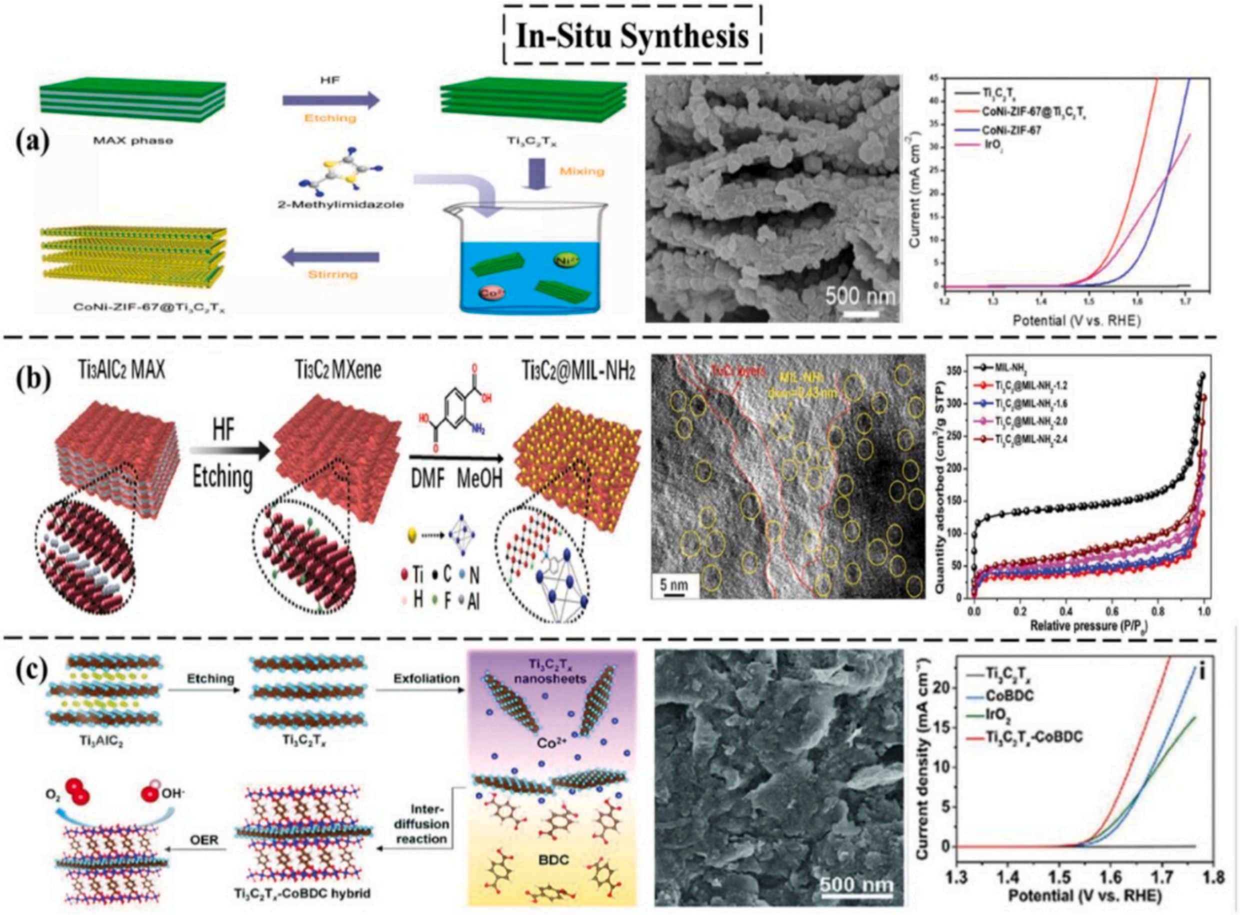


Fig. 13. In-situ growth 3D MXene/MOF composite for high-performance capacitors. Reproduced with permission from the Ref. [236].

integrated with MXene [211]. This approach facilitates the development of cationic polymer-functionalized MOFs that incorporate negatively charged MXene ions. Pang et al. [239] employed ultrasonic-assisted synthesis utilizing high-frequency ultrasonic waves to enhance the chemical reaction involved in MXene@MOF hybridization. This method proved to be easy to implement, cost-effective, and environmentally sustainable [239].

Furthermore, the synthesis of 0D and 2D MXene/Ni-MOF heterojunction catalysis was achieved through the ex-situ method, which involved sonicating the 0D MXene quantum dots alongside the 2D Ni-MOF nanosheet. This process yielded composites characterized by improved absorption and interfacial charge transfer capabilities [240]. Qu et al. [241] explored the development of $Ti_3C_2T_x$ MXene hybrids exhibiting remarkable electrochemical performance by employing the ultrasonic cationic technique, resulting in MXene nanosheets being uniformly distributed on the N-MOF surface [242]. The composite produced was utilized in the creation of supercapacitor electrodes, showcasing outstanding electronic conductivity with a specific capacitance of 867.3F/g at a 1/g rate capacity [241]. The method of electrochemical deposition, in conjunction with electric current, can facilitate the deposition of either MXene or MOF materials onto an electrode surface. By applying a controlled electric potential, layers of MXene or MOF are deposited onto the conductive substrate, leading to the formation of an MXene/MOF hybrid electrode [243]. In comparison to alternative preparation methods, the ex-situ synthesis technique has garnered less focus, potentially due to the inferior homogeneity of the resulting product and the structural degradation of the material under certain conditions [244]. Nevertheless, despite these concerns, physical mixing offers a straightforward approach for composite preparation. When preparing the $Ti_3C_2T_x$ MXene/MIL-53 composite, the in-situ synthesis method is preferred due to the specific properties of interest. In this scenario, the MIL-53 will be cultivated on the MXene surface, allowing for the self-restacking of the $Ti_3C_2T_x$ MXene under meticulously controlled experimental conditions [245]. However, the ex-situ synthesis method can also be utilized to fabricate the (MXene/MOF) composite under stringent and controlled experimental conditions through the ultrasonication technique, thereby validating the product derived from the in-situ synthesis method [246]. The synthesis route strongly dictates the ultimate performance of MXene/MIL-53 hybrids. In-situ methods achieve intimate interfacial bonding but can promote oxidation, while ex-situ strategies enhance structural stability but often reduce homogeneity. Process–structure–property mapping shows that neither approach alone is sufficient to optimize performance. A combined or “semi in-situ” approach, where interfacial bonding occurs during synthesis, followed by controlled post-assembly, represents a promising direction for scalable fabrication of high-performance MXene/MIL-53 composites.

4.6. *Structural engineering and material design considerations*

Structural engineering represents a key lever in optimizing MXene/MOF composites for energy storage [155]. In MXenes, controlling interlayer spacing is essential to suppress restacking and enable rapid ion diffusion, while defect engineering provides additional active sites for charge storage [247]. For MIL-53, the breathing nature of its one-dimensional channels can be tuned to accommodate ion intercalation and mitigate stress during cycling, thereby enhancing structural resilience. Constructing hierarchical or layered architectures that integrate MXene sheets with porous MIL-53 frameworks allows the formation of multidimensional ion-transport pathways, which is critical for achieving both high capacity and long-term stability [13],[248].

At the material design level, surface functionalization of MXenes with –O, –OH, or –F groups not only tailors electronic structure but also strengthens interfacial bonding with MOFs [249]. Similarly, compositional tuning of MIL-53 through metal substitution or linker modification can adjust pore size, redox activity, and chemical stability [250]. These design strategies work synergistically when MXenes provide conductive scaffolds and MIL-53 introduces porosity and flexibility, creating hybrids that outperform either component alone [251]. Beyond conventional mixing, rational design approaches such as ex-situ heterostructure assembly, in-situ growth on MXene surfaces, and defect-controlled interfaces can further optimize charge storage mechanisms [252].

Looking forward, advancing MXene/MIL-53 composites will require a holistic approach that integrates structural engineering and material design across multiple scales [13]. At the atomic level, tailoring surface terminations and controlling defect chemistry can regulate electrochemical kinetics [253]. At the mesoscale, constructing hierarchical architectures and engineered porosity can promote ionic accessibility and durability [254],[255]. At the device level, scalable fabrication techniques such as thin-film deposition, 3D printing, and binder-free electrode processing will be critical to bridge laboratory synthesis with real-world applications [256]. Such multiscale engineering strategies provide a clear roadmap for designing MXene/MIL-53 hybrids capable of delivering the high energy density, power capability, and cycling stability demanded by next-generation energy storage systems.

5. Electrochemical energy retention of various MXene and MOFs composites

Research on the synergistic effects of MXene/MOF composites for electrochemical energy storage highlights the necessity for materials that exhibit improved capacity retention, substantial energy density, and long-term stability in energy storage systems such as capacitors, supercapacitors, and lithium-ion batteries [165],[257]. This review has demonstrated that the combination of these two materials leads to high-performance electrochemical energy storage characterized by enhanced ionic conductivity, prolonged stability, rapid charging rates, excellent capacity retention, and swift ionic diffusion. As illustrated in Table 1, various hybrids of MXenes and MOFs have shown remarkable capacitance with exceptional capacity retention, reaching up to 109 % as reported in some of the reviewed literature. This suggests that with the appropriate synthesis methods, $Ti_3C_2T_x$ MXene@MIL-53 MOF could yield composites with superior electrochemical properties suitable for energy storage applications.

5.1. Characterization techniques of MXene/MOF composites

A variety of characterization techniques have been utilized to investigate and clarify the structural, morphological, and electrochemical properties of the synthesized MXene/MOFs composite [233]. Regrettably, there is a lack of supporting literature regarding the $Ti_3C_2T_x$ MXene and MIL-53 composites, despite the extensive research conducted to comprehend the electrochemical properties of different MXene composites for energy storage applications. This review serves as a reference for future research and interest in the synergistic effects of $Ti_3C_2T_x$ MXene and MIL-53 MOF composites aimed at enhancing electrochemical energy storage systems.

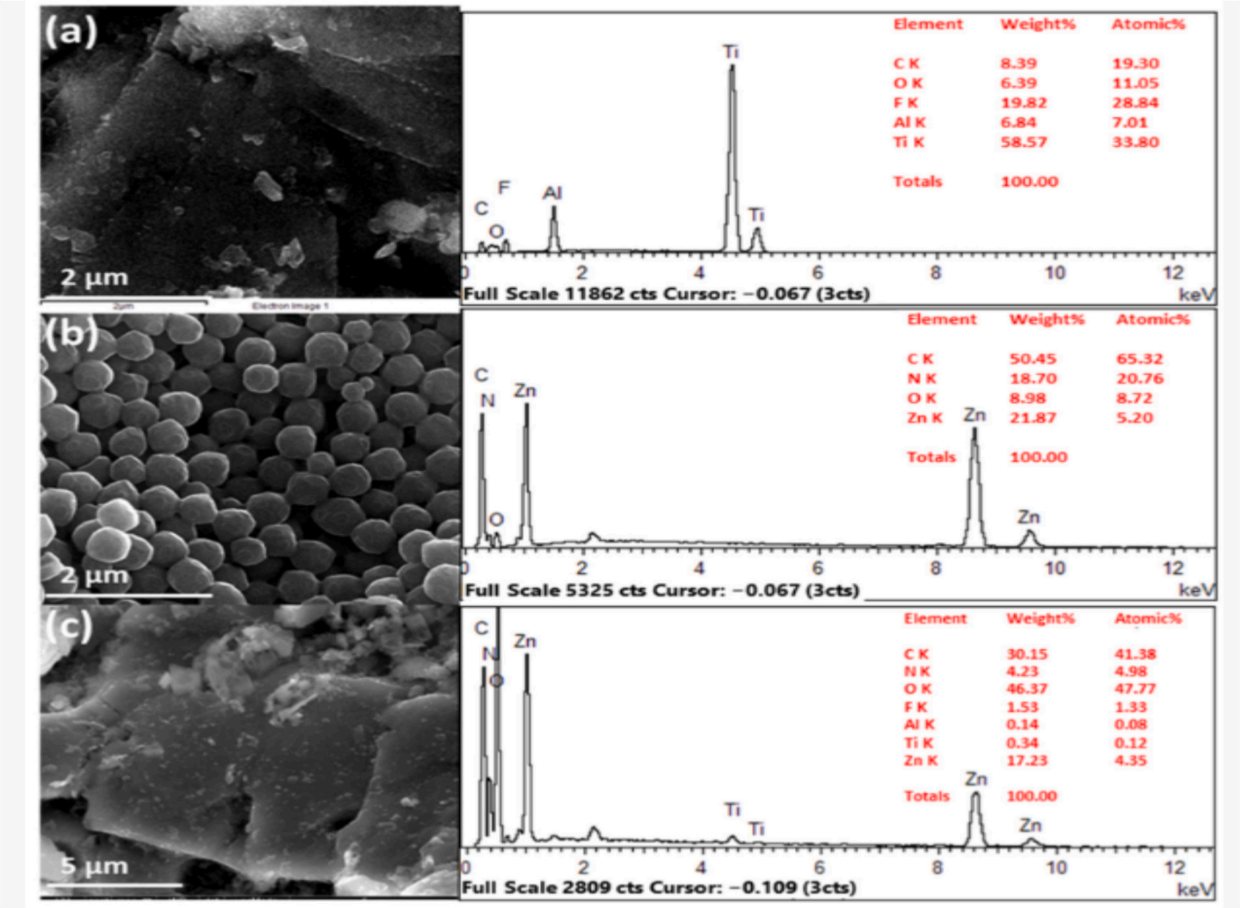
This section delves into various characterization techniques, including X-ray diffraction methods to analyze the crystal structure of the MXene/MOF hybrids, SEM to assess the morphology of the composite, and FTIR techniques [276] that have been employed to confirm the structural integrity and chemical interactions within MXene/MOFs composites. Such analyses will yield insights into the potential electrochemical behavior of $Ti_3C_2T_x$ MXene/MIL-53 hybrid composites for energy storage applications. Fig. 14 illustrate the characterization methods utilized by Hao et al. [277] in their study of the synergistic integration of MXene/MOF ($Ti_3C_2T_x$@ZIF-8) for advanced electrocatalytic hydrogen evolution in an alkaline environment. A $Ti_3C_2T_x$ MXene nanosheet, encapsulated with the MOFs catalyst ($Ti_3C_2T_x$@ZIF-8) by surrounding the precursor with ZIF-8, was synthesized under alkaline conditions. The composite exhibited a 507 mV overpotential at 20 mV/cm, and a CV analysis revealed an electrochemically active surface area of 122.5/cm^2, demonstrating excellent electrochemical characteristics and robust stability, indicating its potential as a candidate for electrochemical energy storage. The findings from this study provide a substantial foundation for understanding the electrochemical behavior of MXene/MOFs composites [277].

5.2. Electrochemical analysis of MXene/MOFs composites

To comprehend the electrochemical energy storage potential of the composites, CV analysis is employed to assess the charge storage capacity and the electrochemical reversibility of the MXene/MOFs composite, utilizing EIS to evaluate the charge transfer resistance and capacitance of various MXene/MOFs composites [278]. This assessment determines the durability of the composite over prolonged charge and discharge cycles, as well as the life cycle analysis of the developed material for energy-related applications. Fig. 15 illustrates the CV analysis conducted by Liu et al. [279] on 3D porous Ti_3C_2 MXene/NiCo-MOF composites aimed at enhancing

Table 1
Capacitance and capacity retention rate of various MXene and MOF hybrids.

Synthesis method	Composite formed	Capacitance and Capacity retention rate	Reference
Reported hydrothermal synthesis method	Ti_3C_2@UiO-66	Up to 92 % after 1000 cycles	Yang et al. [25]
Template free self-assembly	CoN-MOF@$Ti_3C_2T_x$	Retention up to 85 % after 500 cycles	Wu et al. [258]
In-situ method	$Ti_3C_2T_x$@ ZIF-8	1104 mAh/g at 0.1 A/g after 100 cycles	Nahirniak et al. [259]
Solvothermal synthesis approach	$Ti_3C_2T_x$@CNTs	Produced capacitance of 2118 mAh /g at 200 mA /g after 100 life cycles	Ampong et al. [260]
Chemical bonding and sonication techniques	Ni-MOF@$Ti_3C_2T_x$	Up to 88 % capacity retention after 200 cycles	Bibi et al. [211]
Solvothermal synthesis	Zr-MOF@$Ti_3C_2T_x$	80 % capacity retention after 200 cycles	Zhuang et al. [236]
Solution method	PANI@rGO	45.62F/g capacitance up to 84 % capacity retention.	Liu et al. [261]
Chemical etching method	Nb_2C@$Ti_3C_2T_x$	584F/g at 2A/g up to 98 % retention after 50, 000 cycles	Nasrin et al. [227]
Sonication method	$NiFe_2O_4/TiO_4$@Ti_3C_2	90 % capacity retention at 10 mA/g after 500 cycles	Palanisamy et al. [262]
Ex-situ synthesis method	V_2CT_x@ COF	80 % capacity retention	Ramachandran et al. [263]
In-situ synthesis	$Ti_3C_2T_x$@MOF	155 mAh/g capacitance up to 77 % capacity retention	Mousavi and Hosseini [264]
Hydrothermal method	$Ti_3C_2T_x$@ COF	87.5 % retention after 5000 cycles at 5 mA /g	Rostami et al. [158]
Solution synthesis and HF + HCl etching method	$Ti_3C_2T_x$@ ZIF-67	550.6 mAh /g at 10 mA/g	Mane et al. [265]
In-situ growth method	$Ti_3C_2T_x$@ Ni-HHTP	390 mAh /g capacitance at 0.5 mA /g up to 92 % after 800 cycles	Wu et al. [229]
In-situ growth method	$Ti_3C_2T_x$@ Cu-MOF	Capacitance of 726 mAh/g up to 90 %	Phung et al. [266]
Mechanical method	S-MOF@$Ti_3C_2T_x$	675.2 mAh/g capacitance at 1.5 mA/g up to 91 %	Li et al. [267]
In-situ growth	$Ti_3C_2T_x/MoS_2$/Sns@C	Capacitance of 722.4 mAh/g after 50 cycles	Cui et al. [268]
Ex-situ and solvothermal method	$Ti_3C_2T_x/CoSe_2$@ZIF-67 MOF	Capacitance of 75.5 mAh/g at 1000 mA/g up to 79 % after 500 cycles	Liu et al. [269]
Chemical vapor deposition	$Ti_3C_2T_x$@MoS_2	1000 F/cm^3 capacitance up to 92 % retention	Mahajan [270]
Etching method, CVD, and template technique	$Ti_3C_2T_x$@ ZIF-MOF	Up to 86.6 % retention after 500 cycles	Iravani et al. [271]
Ex-situ sonication method	Ti_3C_2@CoNiZn LDH composite	Capacitance of 2044.9F/g up to 87.8 % retention after 1,000,000 cycles	Dai et al. [272]
Sonication method	ZIF-67@NC-Co	Capacitance of 1018.7 mAh/g up to 83.5 % after 100 cycles	Zhang et al. [273]
In-situ growth method	$Ti_3C_2T_x$@MOF	Up to 96 % capacity retention after 10,000 cycles	Alli et al. [274]
Template synthesis technique	MOF-based composite	Capacitance of 75. 59f/g at 1 mA/g up to 99 % retention	Lokhande et al. [275]
Hydrothermal synthesis	Ce-Co-MOFs@$Ti_3C_2T_x$	Specific capacity of 438.3F/g with capacity retention of 109 % after 4000 charge/discharge life cycles	Siddiqui et al. [179]



Element	Weight%	Atomic%
C K	8.39	19.30
O K	6.39	11.05
F K	19.82	28.84
Al K	6.84	7.01
Ti K	58.57	33.80
Totals	100.00	

Element	Weight%	Atomic%
C K	50.45	65.32
N K	18.70	20.76
O K	8.98	8.72
Zn K	21.87	5.20
Totals	100.00	

Element	Weight%	Atomic%
C K	30.15	41.38
N K	4.23	4.98
O K	46.37	47.77
F K	1.53	1.33
Al K	0.14	0.08
Ti K	0.34	0.12
Zn K	17.23	4.35
Totals	100.00	

Fig. 14. SEM and EDS patterns of (a) $Ti_3C_2T_x$, (b) ZIF-8, and (c) $Ti_3C_2T_x$/ZIF-8 composite [277].

lithium-ion storage. The Ti_3C_2/NiCo-MOF electrode demonstrated remarkable reversibility of 402 mAh/g over 300 cycles at 0.1 A/g, along with long-term stability and exceptional capacitance of 256 mAh/g at 1 A/g, achieving 85.7 % retention even after 400 cycles at a current density exceeding that of pure Ti_3C_2 MXene. These results affirm the Ti_3C_2@NiCo-MOF composites as an outstanding material for high-performance energy storage devices. The CV analysis of Ti_3C_2@NiCo-MOF composites as anodic materials for LIBs revealed a material with significant electrochemical storage capacity. As depicted in Fig. 14, a peak at 1.12 V corresponds to the irreversibility associated with the formation of the solid electrolyte interphase [280], while a second peak indicates Li^+ ion trapping between the Ti_3C_2 and NiCo-MOF nanosheets, accounting for 0.6 V.

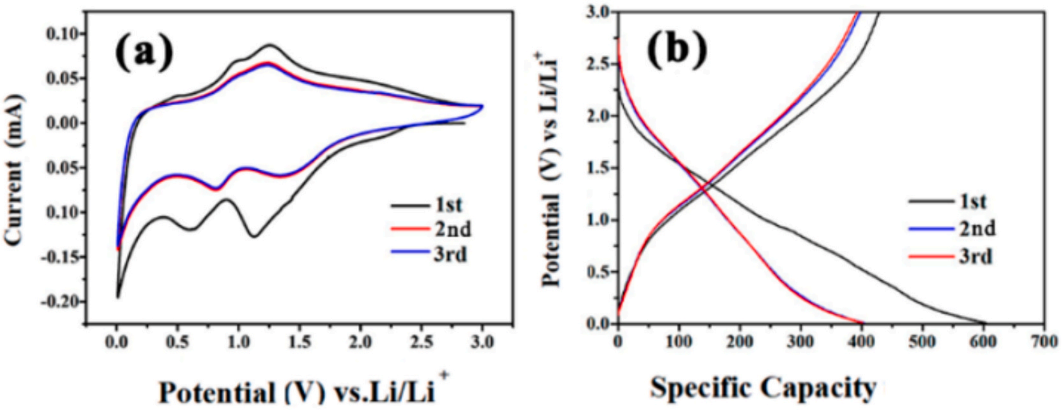


Fig. 15. a) CV profiles of the composites at 0.1 V scanning rates, b) specific capacitance of the composites at different current densities [279].

According to Liu et al. [279], the extraction of Li^+ from Ti_3C_2 and NiCo-MOF nanosheets may lead to significant oxidation–reduction peaks at 1.24 V in the following cycles. Cathodic peaks observed at 0.81 and 1.41 V indicated a transformation of Co and Ni during the second cycle. The second and third cycles appeared to be identical, showcasing a highly reversible electrochemical reaction process of the Ti_3C_2@NiCo-MOF composites. As shown in Fig. 15 the specific capacities for the charge and discharge rates during the first three cycles of the composite at 0.1 A/g, with the initial cycle exhibiting discharge and charge capacities of 603.6 mAh/g and 428.8 mAh/g, respectively. This phenomenon may be attributed to the formation of an electrolyte interphase, which corroborates the CV analysis. The overlap of the composites in the second and third cycles signifies a robust reversibility and stability of the Ti_3C_2/NiCo-MOF composites.

Direct comparison of electrochemical performance across MXene/MOF hybrids reveals that $Ti_3C_2T_x$/MIL-53 composites achieve promising but still developing results relative to other systems [211]. For example, $Ti_3C_2T_x$/MIL-53 hybrids have demonstrated specific capacitance values typically in the range of ~ 300–350F/g with retention rates above 85 % after several thousand cycles, reflecting the beneficial synergy between conductivity and porosity [137]. In contrast, $Ti_3C_2T_x$/UiO-66 and $Ti_3C_2T_x$/ZIF-8 systems often report higher capacitance values exceeding 400F/g with retention above 90 %, largely due to their more extensively engineered interfacial chemistry and hierarchical structures [281]. $Ti_3C_2T_x$/MIL-101 hybrids further extend this trend, showing capacitance values approaching ~ 450F/g with excellent rate capability, attributed to their ultrahigh surface area and robust framework stability [282]. Taken together, these comparisons suggest that while $Ti_3C_2T_x$/MIL-53 demonstrates a favorable balance between conductivity and porosity, further optimization of interfacial design and pore structure is needed to match or surpass the electrochemical performance of other well-studied MXene/MOF composites. Despite its slightly lower capacitance, $Ti_3C_2T_x$/MIL-53 remains highly relevant due to its excellent structural stability, facile synthesis, and potential for scalable fabrication. Its balanced combination of cycling stability, moderate capacitance, and tunable framework makes it a promising candidate for practical energy storage applications where long-term reliability is crucial.

6. Challenges and perspectives of MXene/MOF composites

Although MXene/MOF composites have demonstrated remarkable potential in electrochemical energy storage and related applications, several critical challenges remain unresolved, and these must be addressed before large-scale deployment can be realized. One of the foremost challenges is the intrinsic instability of MXenes toward oxidation, which leads to deterioration of conductivity and structural integrity over time [283]. While temporary remedies such as antioxidant additives or inert atmosphere storage have been explored, there is still a pressing need for robust stabilization strategies that can ensure long-term durability under practical operating conditions [284]. Defect engineering, protective surface coatings, and controlled termination chemistry may provide promising routes, but more systematic investigations are required to translate these laboratory approaches into scalable solutions [285].

A second major challenge lies in the interfacial bonding and compatibility between MXenes and MOFs, which directly governs the electrochemical synergy of the hybrid structures [12]. Weak interfacial interactions can result in structural collapse during charge–discharge cycling, whereas excessively strong bonding may hinder ion transport pathways [286]. Therefore, the rational design of interfaces through functional group matching, heteroatom doping, or covalent cross-linking represents a crucial research direction to strike a balance between structural stability and efficient electrochemical kinetics [287]. In addition, the trade-off between conductivity and porosity remains another obstacle. While MXenes contribute excellent metallic conductivity, they also have a strong tendency to restack, which reduces porosity and ion accessibility [288]. Conversely, MOFs offer high porosity but generally suffer from poor intrinsic conductivity. Achieving an optimum combination requires hierarchical design strategies, such as constructing layered heterostructures or 2D/3D hybrid architectures that can simultaneously deliver ion-accessible channels and conductive pathways [289].

Scalability and sustainability also present significant barriers. Many of the widely adopted synthesis techniques for MXenes still depend on hazardous etchants such as HF or involve multistep solvothermal processes, which limit both industrial applicability and environmental sustainability [83]. To move toward commercialization, it is essential to adopt greener and scalable fabrication methods, such as molten salt etching, electrochemical synthesis, or deep eutectic solvents, in combination with continuous-flow processing [290]. These approaches not only reduce environmental concerns but also offer pathways for producing composites in industrially relevant quantities.

Looking forward, MXene/MOF composites provide a rich landscape of opportunities that extend beyond conventional supercapacitors and ion-batteries. Future perspectives point toward multifunctional energy devices, including hybrid systems that combine the high energy density of batteries with the long cycle life of supercapacitors. Moreover, these hybrids may also find applications in electrocatalysis, CO_2 reduction, water splitting, and ion-sieving membranes, thereby expanding their technological relevance [291]. Coupling experimental work with advanced computational techniques such as density functional theory, molecular dynamics, and machine learning can further accelerate the rational design of composites by predicting optimal interfacial structures, defect chemistries, and performance trends.

Overall, the future of MXene/MOF composites depends on an integrated approach that combines materials engineering, scalable synthesis, and computational modeling. By carefully addressing the issues of stability, interfacial design, conductivity–porosity balance, and environmental sustainability, these materials can be transformed from promising laboratory concepts into practical, high-impact solutions for next-generation energy storage and conversion technologies. Although $Ti_3C_2T_x$/MIL-53 composites have attracted attention conceptually, the experimental validation of their unique synergy remains limited compared to other MXene/MOF systems such as $Ti_3C_2T_x$/UiO-66, $Ti_3C_2T_x$/ZIF-8, and $Ti_3C_2T_x$/MIL-101 [292–294]. The few available studies suggest that $Ti_3C_2T_x$/MIL-53 hybrids benefit from complementary effects, including enhanced interfacial bonding, improved conductivity–porosity balance, and superior ion transport properties [295]. However, these findings are still in the early stages, and systematic investigations into long-term stability, charge storage kinetics, and scalability are required. Recognizing this gap, future research should focus on experimental benchmarking of $Ti_3C_2T_x$/MIL-53 composites, supported by advanced characterization and computational modeling, to fully validate and harness their synergistic potential.

7. Conclusion

Building upon the challenges and future perspectives outlined above, this review has systematically examined the synergistic integration of MXenes and MOFs, with a particular focus on MIL-53 frameworks, and highlighted their potential to overcome the inherent trade-offs between conductivity, porosity, and structural stability in advanced electrochemical energy storage devices. The discussion consolidated synthesis strategies, process–structure–property relationships, and electrochemical performance outcomes, while critically identifying the unresolved issues of MXene oxidation, interfacial compatibility, and scalability of fabrication. The future of MXene/MOF composites will depend not only on improving electrochemical performance at the laboratory scale but also on addressing practical considerations such as environmentally sustainable synthesis routes, long-term structural stability, and scalable processing methods. Furthermore, coupling experimental insights with computational tools such as DFT, molecular dynamics, and machine learning will accelerate rational design strategies, enabling predictive control over interfacial chemistry and hierarchical architectures. Overall, the combination of MXene’s metallic conductivity and surface functionality with the tunable porosity and flexibility of MOFs offers a powerful platform for designing multifunctional materials. By strategically addressing the identified challenges, MXene/MOF composites can transition from emerging research concepts to practical, durable, and sustainable solutions for next-generation energy storage and conversion technologies. In summary, MXene/MOF composites represent a new frontier in materials engineering where conductivity, porosity, and structural adaptability can be synergistically optimized for advanced energy storage. While significant obstacles remain, the pathway forward is clear: stabilization of MXenes, rational interfacial design, scalable green synthesis, and integration with computational modeling. Addressing these priorities will not only unlock the full electrochemical potential of MXene/MOF hybrids but also position them as transformative materials for sustainable energy technologies, bridging the gap between laboratory innovation and industrial application.

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Declaration of competing interest

The authors declare that the work reported in this study was not affected by any conflicting financial interests or personal connections.

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Data availability

No data was used for the research described in this article.

References

[1] Hossain E, Faruque HMR, Sunny MSH, Mohammad N, Nawar N. *A comprehensive review on energy storage systems: Types, comparison, current scenario, applications, barriers, and potential solutions, policies, and future prospects*. Energies 2020;13(14):3651.

[2] Kulkarni AA, Gaikwad NK, Salunkhe AP, Dahotre RM, Bhat TS, Patil PS. *An ensemble of progress and future status of piezo-supercapacitors*. J Storage Mater 2023;65:107362.

[3] Banik U, Malik MTU, Rahat SSM, Mallik AK. *Performance enhancement of ruthenium-based supercapacitors: a review*. Energy Storage 2023;5(3):e380.

[4] Li L, Liu W, Dong H, Gui Q, Hu Z, Li Y, et al. *Surface and interface engineering of nanoarrays toward advanced electrodes and electrochemical energy storage devices*. Adv Mater 2021;33(13):2004959.

[5] Chen M, Zhang Y, Xing G, Chou S-L, Tang Y. *Electrochemical energy storage devices working in extreme conditions*. Energ Environ Sci 2021;14(6):3323–51.

[6] Smdani G, Islam MR, Ahmad Yahaya AN, Bin Safie SI. *Performance evaluation of advanced energy storage systems: a review*. Energy Environ 2023;34(4):1094–141.

[7] Zhang X, Cheng X, Zhang Q. *Nanostructured energy materials for electrochemical energy conversion and storage: a review*. Journal of energy chemistry 2016;25(6):967–84.

[8] Shen X, Liu H, Cheng X-B, Yan C, Huang J-Q. *Beyond lithium ion batteries: Higher energy density battery systems based on lithium metal anodes*. Energy Storage Mater 2018;12:161–75.

[9] He S, Wang S, Chen H, Hou X, Shao Z. *A new dual-ion hybrid energy storage system with energy density comparable to that of ternary lithium ion batteries*. J Mater Chem A 2020;8(5):2571–80.

[10] Wang M, Dong R, Feng X. *Two-dimensional conjugated metal–organic frameworks (2D c-MOFs): chemistry and function for MOFtronics*. Chem Soc Rev 2021;50(4):2764–93.

[11] VahidMohammadi A, Rosen J, Gogotsi Y. *The world of two-dimensional carbides and nitrides (MXenes)*. Science 2021;372(6547).

[12] Saini H, Srinivasan N, Sedajova V, Majumder M, Dubal DP, Otyepka M, et al. *Emerging MXene@ Metal–organic framework hybrids: design strategies toward versatile applications*. ACS Nano 2021;15(12):18742–76.

[13] Farooq K, Murtaza M, Kiran L, Farooq K, Shah WA, Waseem A. *Construction of an MXene/MIL Fe-53/ZIF-67 derived bifunctional electrocatalyst for efficient overall water splitting*. Nanoscale Adv 2025;7(6):1561–71.

[14] Yang L, Cao LN, Li S, Peng P, Qian H, Amaratunga G, et al. *MOFs/MXene nano-hierarchical porous structures for efficient ion dynamics*. Nano Energy 2024;129:110076.

[15] Elalfy DA, Gouda E, Kotb MF, Bureš V, Sedhom BE. *Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends*. Energ Strat Rev 2024;54:101482.

[16] Chemali E, Preindl M, Malysz P, Emadi A. *Electrochemical and electrostatic energy storage and management systems for electric drive vehicles: State-of-the-art review and future trends*. IEEE Journal of Emerging and Selected Topics in Power Electronics 2016;4(3):1117–34.

[17] Aslfattahi N, Kiai MS, Karatas D, Baydogan N, Samylingam L, Kadirgama K, et al. *Interfacial synergy of pre-lithiation silicon anodes and GNP/MnO 2/S cathodes for lithium polysulfides in silicon–sulfur batteries studied via DFT*. Sustainable Energy Fuels 2025;9(8):2137–48.

[18] Schötz T, Gordon LW, Ivanov S, Bund A, Mandler D, Messinger RJ. *Disentangling faradaic, pseudocapacitive, and capacitive charge storage: a tutorial for the characterization of batteries, supercapacitors, and hybrid systems*. Electrochim Acta 2022;412:140072.

[19] Li T, Qin T, Yang C, Zhang W, Zhang W. *Mechanism orienting structure construction of electrodes for aqueous electrochemical energy storage systems: a review*. Nanoscale 2021;13(6):3412–35.

[20] Fleischmann S, Mitchell JB, Wang R, Zhan C, Jiang D-E, Presser V, et al. *Pseudocapacitance: from fundamental understanding to high power energy storage materials*. Chem Rev 2020;120(14):6738–82.

[21] Liu X, Li Y, Xu X, Zhou L, Mai L. *Rechargeable metal (Li, Na, Mg, Al)-sulfur batteries: materials and advances*. Journal of energy chemistry 2021;61:104–34.

[22] Azega R, Smith AD, Chowdhury NR, Vyas A, Li Q, Haque M, et al. *Supercapacitors and rechargeable batteries, a tale of two technologies: past, present and beyond*. Sustain Mater Technol 2024;41:e01111.

[23] Venkateswarlu S, Vallem S, Umer M, Jyothi N, Babu AG, Govindaraju S, et al. *Recent progress on MOF/MXene nanoarchitectures: a new era in coordination chemistry for energy storage and conversion*. Journal of Energy Chemistry 2023;86:409–36.

[24] Ji Y, You Y, Xu G, Yang X, Liu Y. *Engineering metal organic framework (MOF)@ MXene based electrodes for hybrid supercapacitors–a review*. Chem Eng J 2024;483:149365.

[25] Yang Hui, Zhang Guang-Xun, Zhou Hui-Jie, Sun Yue-Yao. *Metal–organic frameworks meet MXene: New opportunities for electrochemical application*. Energy Mater. Adv. 2023;4:0033.

[26] Samylingam I, Kadirgama K, Samylingam L, Aslfattahi N, Ramasamy D, Sazali N, et al. *Review of Ti3C2Tx MXene Nanofluids: Synthesis, Characterization, and applications*. Engineering, Technology & Applied Science Research 2024;14(3):14708–12.

[27] Othman Z, Mackey HR, Mahmoud KA. *A critical overview of MXenes adsorption behavior toward heavy metals*. Chemosphere 2022;295:133849.

[28] Xu J, Peng T, Qin X, Zhang Q, Liu T, Dai W, et al. *Recent advances in 2D MXenes: preparation, intercalation and applications in flexible devices*. J Mater Chem A 2021;9(25):14147–71.

[29] Lim KRG, Shekhirev M, Wyatt BC, Anasori B, Gogotsi Y, Seh ZW. *Fundamentals of MXene synthesis*. Nat Synth 2022;1(8):601–14.

[30] Baig MM, Gul IH, Baig SM, Shahzad F. *2D MXenes: synthesis, properties, and electrochemical energy storage for supercapacitors–a review*. J Electroanal Chem 2022;904:115920.

[31] Ji C, Cui H, Mi H, Yang S. *Applications of 2D MXenes for electrochemical energy conversion and storage*. Energies 2021;14(23):8183.

[32] Shahzad U, Marwani HM, Saeed M, Asiri AM, Rahman MM. *Two-dimensional MXenes as emerging materials: a comprehensive review*. ChemistrySelect 2023;8(25):e202300737.

[33] Bansal S, Chaudhary P, Sharma BB, Saini S, Joshi A. *Review of MXenes and their composites for energy storage applications*. J Storage Mater 2024;87:111420.

[34] Das P, Wu Z-S. *MXene for energy storage: present status and future perspectives*. Journal of Physics: Energy 2020;2(3):032004.

[35] Wang P, Wang B, Wang R. *Progress in the synthesis process and electrocatalytic application of MXene materials*. Materials 2023;16(20):6816.

[36] Yang Q, Dong L, Su R, Hu B, Wang Z, Jin Y, et al. *Nanostructured heterogeneous photo-catalysts for hydrogen production and water splitting: a comprehensive insight*. Appl Mater Today 2019;17:159–82.

[37] Goswami S, Ghosh CK. *Two-dimensional MXenes: fundamentals, characteristics, synthesis methods, processing, compositions, structure, and applications*. MXene Reinforced Polymer Composites: Fabrication, Characterization and Applications 2024:1–38.

[38] Khan K, Tareen AK, Ahmad W, Hussain I, Chaudhry MU, Mahmood A, et al. *Recent advances in Non-Ti MXenes: Synthesis, Properties, and Novel applications*. Adv Sci 2024;11(36):2303998.

[39] Samylingam L, Aslfattahi N, Kok CK, Kadirgama K, Schmirler M, Yusaf T, et al. *Underlying developments in hydrogen production technologies: economic aspects and existent challenges*. Korean J Chem Eng 2024;41(11):2961–84.

[40] Rahman UU, Humayun M, Ghani U, Usman M, Ullah H, Khan A, et al. *MXenes as emerging materials: synthesis, properties, and applications*. Molecules 2022;27(15):4909.

[41] Li S-H, Qi M-Y, Tang Z-R, Xu Y-J. *Nanostructured metal phosphides: from controllable synthesis to sustainable catalysis*. Chem Soc Rev 2021;50(13):7539–86.

[42] Ma P, Fang D, Liu Y, Shang Y, Shi Y, Yang HY. *MXene-based materials for electrochemical sodium-ion storage*. Adv Sci 2021;8(11):2003185.

[43] Dong Y, Shi H, Wu ZS. *Recent advances and promise of MXene-based nanostructures for high-performance metal ion batteries*. Adv Funct Mater 2020;30(47):2000706.
[44] Wu Y, Li X, Zhao H, Yao F, Cao J, Chen Z, et al. *Recent advances in transition metal carbides and nitrides (MXenes): characteristics, environmental remediation and challenges*. Chem Eng J 2021;418:129296.
[45] Tang M, Li J, Wang Y, Han W, Xu S, Lu M, et al. *Surface terminations of MXene: synthesis, characterization, and properties*. Symmetry 2022;14(11):2232.
[46] Wang C, Chen S, Song L. *Tuning 2D MXenes by surface controlling and interlayer engineering: methods, properties, and synchrotron radiation characterizations*. Adv Funct Mater 2020;30(47):2000869.
[47] Sarycheva, A. and Y. Gogotsi, *Raman spectroscopy analysis of the structure and surface chemistry of Ti3C2Tx MXene*, in *MXenes*. 2023, Jenny Stanford Publishing. p. 333-355.
[48] Zhao Y, Zhou F, Liang Q, Zhang B, Wang P, Lv Q, et al. *Intercalating anion and hydrogen-bond network in layered double hydroxide to breakthrough the diffusion limit for unsealing theoretical capacity*. Chem Eng J 2025;505:159398.
[49] Mao L, Qian J. *Interfacial engineering of heterogeneous reactions for MOF-on-MOF Heterostructures*. Small 2024;20(20):2308732.
[50] Bradshaw D, Garai A, Huo J. *Metal–organic framework growth at functional interfaces: thin films and composites for diverse applications*. Chem Soc Rev 2012;41(6):2344–81.
[51] Saha R, García CJG. *Extrinsically conducting MOFs: guest-promoted enhancement of electrical conductivity, thin film fabrication and applications*. Chem Soc Rev 2024.
[52] Tahir B, Alraeesi A, Tahir M. *Metal-organic framework (MOF) integrated Ti3C2 MXene composites for CO2 reduction and hydrogen production applications: a review on recent advances and future perspectives*. Front Chem 2024;12:1448700.
[53] Chaudhary V, Ashraf N, Khalid M, Walvekar R, Yang Y, Kaushik A, et al. *Emergence of MXene–polymer hybrid nanocomposites as high-performance next-generation chemiresistors for efficient air quality monitoring*. Adv Funct Mater 2022;32(33):2112913.
[54] Fan WK, Sherryna A, Tahir M. *Advances in titanium carbide (Ti3C2T x) MXenes and their metal–organic framework (MOF)-based nanotextures for solar energy applications: a review*. ACS Omega 2022;7(43):38158–92.
[55] Sher F, Hayward A, El Guerraf A, Wang B, Ziani I, Hrnjić H, et al. *Advanced metal–organic frameworks for superior carbon capture, high-performance energy storage and environmental photocatalysis–a critical review*. J Mater Chem A 2024;12(41):27932–73.
[56] Li M, Fan Q, Gao L, Liang K, Huang Q. *Chemical intercalation of layered materials: from structure tailoring to applications*. Adv Mater 2024;36(37):2312918.
[57] Wei F, Zhang T, Dong R, Wu Y, Li W, Fu J, et al. *Solution-based self-assembly synthesis of two-dimensional-ordered mesoporous conducting polymer nanosheets with versatile properties*. Nat Protoc 2023;18(8):2459–84.
[58] Cao W, Nie J, Cao Y, Gao C, Wang M, Wang W, et al. *A review of how to improve Ti3C2Tx MXene stability*. Chem Eng J 2024;496:154097.
[59] Wang S, Liu Y, Liu Y, Shi Z, Zhou J, Zhu J, et al. *Identifying the surface properties of Ti3C2Tx MXene through transmission electron microscopy*. Cell Rep Phys Sci 2022;3(11).
[60] Tan K, Samylingam L, Aslfattahi N, Johan MR, Saidur R. *Investigation of improved optical and conductivity properties of poly (methyl methacrylate)–MXenes (PMMA–MXenes) nanocomposite thin films for optoelectronic applications*. Open Chem 2022;20(1):1416–31.
[61] Feng A, Hou T, Jia Z, Zhang Y, Zhang F, Wu G. *Preparation and characterization of epoxy resin filled with Ti3C2Tx MXene nanosheets with excellent electric conductivity*. Nanomaterials 2020;10(1):162.
[62] Liu X, Zheng B, Hua Y, Lu S, Nong Z, Wang J, et al. *Ultralight MXene/rGO aerogel frames with component and structure controlled electromagnetic wave absorption by direct ink writing*. Carbon 2024;230:119650.
[63] Shahzad A, Nawaz M, Moztahida M, Jang J, Tahir K, Kim J, et al. *Ti3C2Tx MXene core-shell spheres for ultrahigh removal of mercuric ions*. Chem Eng J 2019;368:400–8.
[64] Zhan H, Gao L, Li J, Zhang C, Wu Y, Tan M, et al. *Potassium regulated Na4MnV (PO4) 3 microspheres cathode towards robust sodium ion batteries*. Vacuum 2025;233:113947.
[65] Zhao L, Bi S, Li J, Wen Y, Zhang H, Zhang D, et al. *Prussian blue analogues for advanced non-aqueous sodium ion batteries: Redox mechanisms, key challenges and modification strategies*. Energy Storage Mater 2025:104256.
[66] Gentile A, Ferrara C, Tosoni S, Balordi M, Marchionna S, Cernuschi F, et al. *Enhanced functional properties of Ti3C2Tx MXenes as negative electrodes in sodium-ion batteries by chemical tuning*. Small Methods 2020;4(9):2000314.
[67] Hong W, Wyatt BC, Nemani SK, Anasori B. *Double transition-metal MXenes: Atomistic design of two-dimensional carbides and nitrides*. MRS Bull 2020;45(10):850–61.
[68] Naguib M, Barsoum MW, Gogotsi Y. *Ten years of progress in the synthesis and development of MXenes*. Adv Mater 2021;33(39):2103393.
[69] Pandey, M., K. Gong, D. Jayan K, and K. Zhou, *Synthesis approaches of MXene based polymeric nano system for electromagnetic shielding Application-A review*. Critical Reviews in Solid State and Materials Sciences, 2024. **49**(4): p. 754-805.
[70] Iravani S. *MXenes and MXene-based (nano) structures: a perspective on greener synthesis and biomedical prospects*. Ceram Int 2022;48(17):24144–56.
[71] Saxena S, Johnson M, Dixit F, Zimmermann K, Chaudhuri S, Kaka F, et al. *Thinking green with 2-D and 3-D MXenes: Environment friendly synthesis and industrial scale applications and global impact*. Renew Sustain Energy Rev 2023;178:113238.
[72] Solangi NH, Mubarak NM, Karri RR, Mazari SA, Koduru JR. *Recent development of graphene and MXene-based nanomaterials for proton exchange membrane fuel cells*. Int J Hydrogen Energy 2024;73:905–31.
[73] Gong K, Yin L, Zhou K. *Chemical exfoliation and delamination methods of MXenes*. In: MXene reinforced polymer composites: fabrication, characterization and applications; 2024. p. 39–70.
[74] Abbasi NM, Xiao Y, Peng L, Duo Y, Wang L, Zhang L, et al. *Recent advancement for the synthesis of MXene derivatives and their sensing protocol*. Adv Mater Technol 2021;6(10):2001197.
[75] Zhang T, Pan L, Tang H, Du F, Guo Y, Qiu T, et al. *Synthesis of two-dimensional Ti3C2Tx MXene using HCl+ LiF etchant: enhanced exfoliation and delamination*. J Alloy Compd 2017;695:818–26.
[76] Abdullah N, Ishak NAIM, Tan K, Zaed M, Saidur R, Pandey A. *Investigating the impact of various etching agents on Ti3C2Tx MXene synthesis for electrochemical energy conversion*. FlatChem 2024;47:100730.
[77] Jayakumar S, Santhosh PC, Ramakrishna S, Radhamani A. *2D (Ti3C2Tx) MXene: a comprehensive review of advancements in synthesis protocols, applications in supercapacitors, sustainability targets and future prospects*. J Storage Mater 2024;97:112741.
[78] Naguib M, Kurtoglu M, Presser V, Lu J, Niu J, Heon M, Hultman L, Gogotsi Y, Barsoum MW. Two-dimensional nanocrystals produced by exfoliation of Ti_3AlC_2. Adv. Mater. 2011;23:4248–53.
[79] Gandla D, Zhuang Z, Jadhav VV, Tan DQ. *Lewis acid molten salt method for 2D MXene synthesis and energy storage applications: a review*. Energy Storage Mater 2023;63:102977.
[80] Zhang Z, Ji Y, Jiang Q, Xia C. *Molten-salt synthesized MXene for catalytic applications: a review*. Chem Phys Rev 2024;5(3).
[81] Liu L, Orbay M, Luo S, Duluard S, Shao H, Harmel J, et al. *Exfoliation and delamination of Ti3C2T x MXene prepared via molten salt etching route*. ACS Nano 2021;16(1):111–8.
[82] Shen M, Jiang W, Liang K, Zhao S, Tang R, Zhang L, et al. *One-pot green process to synthesize MXene with controllable surface terminations using molten salts*. Angew Chem 2021;133(52):27219–24.
[83] Kumar S. *Fluorine-free MXenes: recent advances, synthesis strategies, and mechanisms*. Small 2024;20(16):2308225.
[84] von Treifeldt JE, Firestein KL, Fernando JF, Zhang C, Siriwardena DP, Lewis C-E-M, et al. *The effect of Ti3AlC2 MAX phase synthetic history on the structure and electrochemical properties of resultant Ti3C2 MXenes*. Mater Des 2021;199:109403.
[85] Yin T, Li Y, Wang R, Al-Hartomy OA, Al-Ghamdi A, Wageh S, et al. *Synthesis of Ti3C2Fx MXene with controllable fluorination by electrochemical etching for lithium-ion batteries applications*. Ceram Int 2021;47(20):28642–9.
[86] Chen J, Chen M, Zhou W, Xu X, Liu B, Zhang W, et al. *Simplified synthesis of fluoride-free Ti3C2T x via electrochemical etching toward high-performance electrochemical capacitors*. ACS Nano 2022;16(2):2461–70.

[87] Wu M, He Y, Wang L, Xia Q, Zhou A. *Synthesis and electrochemical properties of V2C MXene by etching in opened/closed environments*. J Adv Ceram 2020;9(6):749–58.
[88] Murugesan M, Nagavenkatesh K, Devendran P, Nallamuthu N, Sambathkumar C, Kumar MK. *Scalable synthesis of 2D-layered Ti3C2 MXene by HF etching method; electrochemical investigations and device fabrication to enhancing capacitive nature*. Mater Sci Eng B 2024;309:117607.
[89] Raisi B, Huang L, Ye Z. *Modification of Ti 3 C 2 T x MXene with hyperbranched polyethylene ionomers: stable dispersions in nonpolar/low-polarity organic solvents, oxidation protection, and potential application in supercapacitors*. J Mater Chem A 2023;11(32):17167–87.
[90] Natu V, Pai R, Sokol M, Carey M, Kalra V, Barsoum MW. *2D Ti3C2Tz MXene synthesized by water-free etching of Ti3AlC2 in polar organic solvents*. Chem 2020;6(3):616–30.
[91] Gao L, Zhan H, Zhang C, Cao M. *Engineering interleaved large and small Na4MnV (PO4) 3@ NC microspheres cathode towards high performance sodium ion batteries*. Diam Relat Mater 2024;148:111453.
[92] Gong S, Zhao F, Zhang Y, Xu H, Li M, Qi J, et al. *Few-layered Ti3C2Tx MXene synthesized via water-free etching toward high-performance supercapacitors*. J Colloid Interface Sci 2023;632:216–22.
[93] Yao L, Qian L, Song W, Zhang S, Zhang Y, Zhang L, et al. *Advancements in Ti3C2T x MXene Stability: Synergistic Antioxidant strategies and their Impact on Long-Lasting Flexible Sensors*. ACS Appl Mater Interfaces 2024;16(36):48147–62.
[94] Chakraborty G, Park I-H, Medishetty R, Vittal JJ. *Two-dimensional metal-organic framework materials: synthesis, structures, properties and applications*. Chem Rev 2021;121(7):3751–891.
[95] Chen Z, Kirlikovali KO, Li P, Farha OK. *Reticular chemistry for highly porous metal–organic frameworks: the chemistry and applications*. Acc Chem Res 2022;55(4):579–91.
[96] Cai G, Yan P, Zhang L, Zhou H-C, Jiang H-L. *Metal–organic framework-based hierarchically porous materials: synthesis and applications*. Chem Rev 2021;121(20):12278–326.
[97] Song K, Feng X, Zhang N, Ma D, Shi L, Chen Y, et al. *Metal-organic framework materials in NH3-SCR: Progress and prospects*. Coord Chem Rev 2025;535:216615.
[98] Chuhadiya S, Suthar D, Patel S, Dhaka M. *Metal organic frameworks as hybrid porous materials for energy storage and conversion devices: a review*. Coord Chem Rev 2021;446:214115.
[99] Li W, Zhao X, Bi Q, Ma Q, Han L, Tao K. *Recent advances in metal–organic framework-based electrode materials for supercapacitors*. Dalton Trans 2021;50(34):11701–10.
[100] Guo Y, Wang K, Hong Y, Wu H, Zhang Q. *Recent progress on pristine two-dimensional metal–organic frameworks as active components in supercapacitors*. Dalton Trans 2021;50(33):11331–46.
[101] Chen L, Wang H-F, Li C, Xu Q. *Bimetallic metal–organic frameworks and their derivatives*. Chem Sci 2020;11(21):5369–403.
[102] Głowniak S, Szczęśniak B, Choma J, Jaroniec M. *Advances in microwave synthesis of nanoporous materials*. Adv Mater 2021;33(48):2103477.
[103] Hayat A, Rauf S, Al Alwan B, El Jery A, Almuqati N, Melhi S, et al. *Recent advance in MOFs and MOF-based composites: synthesis, properties, and applications*. Mater Today Energy 2024;41:101542.
[104] Makgopa K, Ratsoma MS, Modibane KD. *Intrinsic properties of metal–organic frameworks (MOFs) in supercapacitor applications*. Curr Opin Electrochem 2022;36:101112.
[105] Bian Y, Xie L, Ma L, Cui C. *A novel two-stage energy sharing model for data center cluster considering integrated demand response of multiple loads*. Appl Energy 2025;384:125454.
[106] Senkovska I, Bon V, Abylgazina L, Mendt M, Berger J, Kieslich G, et al. *Understanding MOF flexibility: an analysis focused on pillared layer MOFs as a model system*. Angew Chem 2023;135(33):e202218076.
[107] Seth S, Jhulki S. *Porous flexible frameworks: origins of flexibility and applications*. Mater Horiz 2021;8(3):700–27.
[108] Hou J, Zhang H, Thornton AW, Hill AJ, Wang H, Konstas K. *Lithium extraction by emerging metal–organic framework-based membranes*. Adv Funct Mater 2021;31(46):2105991.
[109] Tomar S, Singh V. *Review on synthesis and application of MIL-53*. Mater Today Proc 2021;43:3291–6.
[110] Yang L, Liu S, Zhang H, Zhang W, Ding W, Zheng H, et al. *Insight into the purification of arsenic-contaminated acid water by metal–organic framework MIL-53 (Fe) with sulfite: the generation and effect of Fe (IV)*. Chem Eng J 2024;481:148766.
[111] Peng X. *Impact of realistic vs. Slit models of activated carbon on H2 and H2S Adsorption, and H2/CO2, CH4/H2S separation*. Sep Purif Technol 2024;338:126538.
[112] Li F, Wang G, Ren J, Sun C. *Synthesis methods and influencing factors of metal organic framework material MIL-53. Journal of Physics: Conference Series*. IOP Publishing; 2022.
[113] Ghasemzadeh MA, Mirhosseini-Eshkevari B, Abdollahi-Basir MH. *MIL-53 (Fe) metal–organic frameworks (MOFs) as an efficient and reusable catalyst for the one-pot four-component synthesis of pyrano [2, 3-c]-pyrazoles*. Appl Organomet Chem 2019;33(1):e4679.
[114] Chen W, Du L, Wu C. *Hydrothermal synthesis of MOFs*. In: *Metal-organic frameworks for biomedical applications*. Elsevier; 2020. p. 141–57.
[115] Kang Z, Chen M, Lin E, Wu J, Ke K, Qin N, et al. *Functionalized MIL-53 and its derivatives modified Bi2WO6 as effective piezocatalysts and membranes for adsorption and decomposition of organic pollutants*. Sep Purif Technol 2023;306:122618.
[116] Muslim M, Ali A, Ahmad M. *Hydrothermal synthesis of metal–organic frameworks*. In: *Synthesis of Metal-Organic Frameworks Via Water-based Routes*. Elsevier; 2024. p. 73–92.
[117] Abdollahi B, Zarei M, Salari D. *Synthesis, characterization, and application of diethylenetriamine functionalized MIL-53 (Fe) metal-organic framework for efficient As (V) removal from surface and groundwater*. J Solid State Chem 2022;311:123132.
[118] Ghanbarian M, Zeinali S, Mostafavi A, Shamspur T. *Facile synthesis of MIL-53 (Fe) by microwave irradiation and its application for robust removal of heavy metals from aqueous solution by experimental design approach: kinetic and equilibrium*. Analytical and Bioanalytical Chemistry Research 2020;7(2):263–80.
[119] Mendes RF, Rocha J, Paz FAA. *Microwave synthesis of metal-organic frameworks*. In: *Metal-organic frameworks for biomedical applications*. Elsevier; 2020. p. 159–76.
[120] Sun L, Yin M, Li Z, Tang S. *Facile microwave-assisted solvothermal synthesis of rod-like aluminum terephthalate [MIL-53 (Al)] for CO2 adsorption*. J Ind Eng Chem 2022;112:279–86.
[121] Chakhtouna, H., H. Benzeid, N. Zari, A. el kacem Qaiss, and R. Bouhfid, Microwave-assisted synthesis of MIL–53 (Fe)/biochar composite from date palm for ciprofloxacin and ofloxacin antibiotics removal. Separation and Purification Technology, 2023. **308**: p. 122850.
[122] Singh R, Kumar R, Singh D, Savu R, Moshkalev S. *Progress in microwave-assisted synthesis of quantum dots (graphene/carbon/semiconducting) for bioapplications: a review*. Mater Today Chem 2019;12:282–314.
[123] Kumar A, Dutta S, Kim S, Kwon T, Patil SS, Kumari N, et al. *Solid-state reaction synthesis of nanoscale materials: strategies and applications*. Chem Rev 2022;122(15):12748–863.
[124] Phan PT, Hong J, Tran N, Le TH. *The properties of microwave-assisted synthesis of metal–organic frameworks and their applications*. Nanomaterials 2023;13(2):352.
[125] Rashid U, Ma X, Zhu Y, Cao C, Zou M. *The Comprehensive Review of Cobalt based Electrocatalysts Synthesized via new Microwave Assisted Methodology*. Mater Chem Front 2025.
[126] Ran S, Sun K, Zhao M, Wang Z, Alshammari AS, Helal MH, et al. *Metal-organic framework derived carbon-based composites for high-performance microwave absorption*. Adv Compos Hybrid Mater 2025;8(1):70.
[127] Głowniak S, Szczęśniak B, Choma J, Jaroniec M. *Mechanochemistry: Toward green synthesis of metal–organic frameworks*. Mater Today 2021;46:109–24.
[128] Tao C-A, Wang J-F. *Synthesis of metal organic frameworks by ball-milling*. Crystals 2020;11(1):15.
[129] Naskar I, Naskar S, Kaur B, Ghosal P, Deepa M. *MIL-53 (Al) metal-organic framework/carbon nanofibers and Al-nanoflakes/carbon composites for a stable Al-battery*. J Storage Mater 2024;77:109956.
[130] Chen Y, Du W, Dou B, Chen J, Hu L, Zeb A, et al. *Metal–organic frameworks and their derivatives as electrode materials for Li-ion batteries: a mini review*. CrstEngComm 2022;24(15):2729–43.

[131] Zhang L, Liu H, Shi W, Cheng P. *Synthesis strategies and potential applications of metal-organic frameworks for electrode materials for rechargeable lithium ion batteries*. Coord Chem Rev 2019;388:293–309.

[132] Theprattanakorn D, Pongha S, Wannasen L, Mongkolthanaruk W, Meethong N, Swatsitang E, et al. *Fe metal-organic framework/pyrolyzed bacterial cellulose composite as a high-performance anode for lithium-ion batteries*. Int J Energy Res 2022;46(13):18328–41.

[133] Liu C, Yuan J, Masse R, Jia X, Bi W, Neale Z, et al. *Interphases, interfaces, and surfaces of active materials in rechargeable batteries and perovskite solar cells*. Adv Mater 2021;33(22):1905245.

[134] Zhou X, Li J, Dong H, Luo Y, Liu C, Huang Y, et al. *MIL-53 (Fe) anode for lithium-ion batteries with the capacity self-activation effect based on electrochemically induced crystalline-to-amorphization transformation*. Mater Today Commun 2024;38:108200.

[135] Simani M, Dehghani H. *The study of electrochemical hydrogen storage behavior of the MIL-53 (M= Cu, Al, Fe and Cr) framework on the Ag/f-MWCNTs substrate*. Fuel 2024;378:132942.

[136] Wang H, Jiang L, Chen J, Fu M, Diao Z, Liu H, et al. *Enhanced bioelectrochemical performance caused by porous metal-organic framework MIL-53 (Fe) as the catalyst in microbial fuel cells*. Process Biochem 2020;99:147–53.

[137] Ojha M, Wu B, Deepa M. *Cost-effective MIL-53 (Cr) metal–organic framework-based supercapacitors encompassing fast-ion (Li+/H+/Na+) conductors*. ACS Appl Energy Mater 2021;4(5):4729–43.

[138] Wang T, Chen S, Chen KJ. *Metal-Organic Framework Composites and their Derivatives as Efficient Electrodes for Energy Storage applications: recent Progress and Future Perspectives*. Chem Rec 2023;23(6):e202300006.

[139] Jiang Q, Zhang H, Ren Z, Ma H, Xue M. *Recent progresses of metal-organic framework-based materials in electrochemical energy storage*. Mater Today Sustainability 2022;19:100174.

[140] Tomar S, Singh V. *Facile synthesis of Bismuth Tungstate modified MIL-53 (Al) and its application for electrochemical energy storage device*. J Indian Chem Soc 2023;100(6):101021.

[141] Tran HV, Dang HTM, Tran LT, Van Tran C, Huynh CD. *Metal-organic framework MIL-53 (Fe): Synthesis, electrochemical characterization, and application in development of a novel and sensitive electrochemical sensor for detection of cadmium ions in aqueous solutions*. Adv Polym Tech 2020;2020(1):6279278.

[142] Xin R, Wang C, Zhang Y, Peng R, Li R, Wang J, et al. *Efficient removal of greenhouse gases: machine learning-assisted exploration of metal–organic framework space*. ACS Nano 2024;18(30):19403–22.

[143] Zhang H, Xu K, He F, Zhu F, Zhou Y, Yuan W, et al. *Challenges and advancements in the electrochemical utilization of ammonia using solid oxide fuel cells*. Adv Mater 2024;36(33):2313966.

[144] Zhang T, Yu J, Guo H, Qi J, Che M, Hou M, et al. *Sapiential battery systems: beyond traditional electrochemical energy*. Chem Soc Rev 2024.

[145] Zhao J, Ma N, Wang T, Wang Y, Liang B, Zhang Y, et al. *Theoretical insights and design of MXene for aqueous batteries and supercapacitors: status, challenges, and perspectives*. Nanoscale Horiz 2025;10(1):78–103.

[146] Bhamare UU, Patil VK, Chaudhari CJ, Patel GM, Palkar MB. *Exploring the emerging technological expansions of MXenes-based nanomaterials: a comprehensive review*. Compos Interfaces 2025:1–57.

[147] Fredj Z, Saadi D. *Utility of MXenes and its Hybrid Materials for Batteries*. In: *MXenes: Expanding the Frontiers of Energy Applications*. Springer; 2025. p. 119–54.

[148] Khanam Z, Gogoi N, Srivastava DN. *Prospective on 2D nanomaterials for energy and environment: challenges, commercial aspect, and the future research endeavor*. In: *2D Nanomaterials for Energy and Environmental Sustainability*. Springer; 2022. p. 267–329.

[149] Del Bosque A, Lampropoulos G, Vergara D. *Nanocomposites for Multifunctional Sensors: a Comprehensive Bibliometric Exploration*. Nanomaterials 2024;15(1):34.

[150] Hu Y, Hong T, Zhou S, Wang Y, Ye Q, Sheng S, et al. *Bibliometric Analysis of Coating Protection from 2015 to 2025*. Coatings 2025;15(6):686.

[151] Tahir M, Ali Khan A, Tasleem S, Mansoor R, Fan WK. *Titanium carbide (Ti3C2) MXene as a promising co-catalyst for photocatalytic CO2 conversion to energy-efficient fuels: a review*. Energy Fuel 2021;35(13):10374–404.

[152] Han Q, Sheng Y, Liu X, Zhang X, Chen X, Li B, et al. *Carbon fiber reinforced epoxy composite combining superior electrochemical energy storage and mechanical performance*. Chem Eng J 2022;437:135228.

[153] Pang J, Mendes RG, Bachmatiuk A, Zhao L, Ta HQ, Gemming T, et al. *Applications of 2D MXenes in energy conversion and storage systems*. Chem Soc Rev 2019;48(1):72–133.

[154] Lokhande P, Pakdel A, Pathan H, Kumar D, Vo D-V-N, Al-Gheethi A, et al. *Prospects of MXenes in energy storage applications*. Chemosphere 2022;297:134225.

[155] Feng S, Wen S, Wang R, Yang X, Yuan X, Liu Y, et al. *MXene/MOF-Derived Composites with Multidimensional Nanostructures: Synthesis Methods, Performance, and applications in the Field of Energy Storage*. Nanomaterials 2025;15(11):841.

[156] Bibi F, Soomro IA, Hanan A, Lakhan MN, Khan A, Goraya NR, et al. *Advances in 2D/2D MXenes-based heterostructures for energy storage/conversion applications*. Journal of Materials Science & Technology 2024;202:82–118.

[157] Hussain I, Lamiel C, Javed MS, Ahmad M, Sahoo S, Chen X, et al. *MXene-based heterostructures: current trend and development in electrochemical energy storage devices*. Prog Energy Combust Sci 2023;97:101097.

[158] Rostami M, Rezvaninia P, Amiri A, Ziarani GM, Ganjali MR, Badiei A. *Hybrid nano-architectural engineering of Ti3C2Tx MXene heterostructures for supercapacitor applications: a review*. Results Eng 2024;22:102227.

[159] Meng W, Liu X, Song H, Xie Y, Shi X, Dargusch M, et al. *Advances and challenges in 2D MXenes: from structures to energy storage and conversions*. Nano Today 2021;40:101273.

[160] Zhu Q, Li J, Simon P, Xu B. *Two-dimensional MXenes for electrochemical capacitor applications: Progress, challenges and perspectives*. Energy Storage Mater 2021;35:630–60.

[161] Hussain I, Bibi F, Pandiyarajan S, Hanan A, Chuang H-C, Zhang K. *Partially oxidized MXenes for energy storage applications*. Prog Mater Sci 2025;147:101351.

[162] Nabeela K, Deka R, Abbas Z, Kumar P, Saraf M, Mobin SM. *Covalent organic frameworks (COFs)/MXenes heterostructures for electrochemical energy storage*. Cryst Growth Des 2023;23(5):3057–78.

[163] Gopalakrishnan M, Kao-ian W, Aupama V, Etesami M, Ganesan S, Theerthagiri J, et al. *Metal-organic framework/mxene heterostructure and its derivatives as electrode materials for rechargeable Zn-based batteries: Design strategies and perspectives*. Chem Eng J 2024;484:149624.

[164] Yang Z, Weng C, Gao X, Meng F, Ji Y, Li J, et al. *In situ construction of Sn-based metal–organic frameworks on MXene achieving fast electron transfer for rapid lithium storage*. Chem Eng J 2024;486:150299.

[165] Shah SS, Aziz MA, Rasool PI, Mohmand NZK, Khan AJ, Ullah H, et al. *Electrochemical synergy and future prospects: Advancements and challenges in MXene and MOFs composites for hybrid supercapacitors*. Sustain Mater Technol 2024;39:e00814.

[166] Najam T, Shah SSA, Peng L, Javed MS, Imran M, Zhao M-Q, et al. *Synthesis and nano-engineering of MXenes for energy conversion and storage applications: recent advances and perspectives*. Coord Chem Rev 2022;454:214339.

[167] Fattah-alhosseini A, Sangarimotlagh Z, Karbasi M. *Latest progress in photocatalytic hydrogen production using MXene (Ti3C2)/MOFs composite: a review*. Int J Hydrogen Energy 2024;79:771–90.

[168] VahidMohammadi A, Liang W, Mojtabavi M, Wanunu M, Beidaghi M. *2D titanium and vanadium carbide MXene heterostructures for electrochemical energy storage*. Energy Storage Mater 2021;41:554–62.

[169] Gaba L, Siwach P, Aggarwal K, Dahiya S, Punia R, Maan A, et al. *Hybridization of metal-organic frameworks and MXenes: Expanding horizons in supercapacitor applications*. Adv Colloid Interface Sci 2024;332:103268.

[170] Kumar YA, Reddy GR, Ramachandran T, Kulurumotlakatla DK, Abd-Rabboh HS, Hafez AAA, et al. *Supercharging the future: MOF-2D MXenes supercapacitors for sustainable energy storage*. J Storage Mater 2024;80:110303.

[171] Zhang F, Qian Y, Jin Z, Fei Z, Zhang J, Mao H, et al. *Recent advances in MOFs/MXenes composites: synthesis and their electrochemical energy applications*. J Storage Mater 2023;72:108213.

[172] Wang T, Lei J, Wang Y, Pang L, Pan F, Chen KJ, et al. *Approaches to enhancing electrical conductivity of pristine metal–organic frameworks for supercapacitor applications*. Small 2022;18(32):2203307.

[173] Zhao T, Yang D, Hao S-M, Xu T, Zhang M, Zhou W, et al. *Optimized electron/ion transport by constructing radially oriented channels in MXene hybrid fiber electrodes for high-performance supercapacitors at low temperatures.* J Mater Chem A 2023;11(4):1742–55.

[174] Idumah CI. *Influence of surfaces and interfaces on MXene and MXene hybrid polymeric nanoarchitectures, properties, and applications.* J Mater Sci 2022;57(31):14579–619.

[175] Simon P, Gogotsi Y. *Perspectives for electrochemical capacitors and related devices.* Nat Mater 2020;19(11):1151–63.

[176] Wu Q, He T, Zhang Y, Zhang J, Wang Z, Liu Y, et al. *Cyclic stability of supercapacitors: materials, energy storage mechanism, test methods, and device.* J Mater Chem A 2021;9(43):24094–147.

[177] Yu L, Chen GZ. *Supercapatteries as high-performance electrochemical energy storage devices.* Electrochem Energy Rev 2020;3(2):271–85.

[178] Khosroshahi N, Bakhtian M, Asadi A, Safarifard V. *Revolutionizing energy storage: the emergence of MOF/MXene composites as promising supercapacitors.* Nano Express 2023;4(4):042002.

[179] Siddiqui, R., M. Rani, A.A. Shah, S. Siddique, and A. Ibrahim, RETRACTED: Enhanced electrochemical performance with exceptional capacitive retention in Ce–Co MOFs/Ti3C2Tx nanocomposite for advanced supercapacitor applications. Heliyon, 2024. **10**(17).

[180] Sharma K, Hasija V, Patial S, Singh P, Nguyen V-H, Nadda AK, et al. *Recent progress on MXenes and MOFs hybrids: structure, synthetic strategies and catalytic water splitting.* Int J Hydrogen Energy 2023;48(17):6560–74.

[181] Wang Z, Liu L, Li Z, Goyal N, Du T, He J, et al. *Shaping of metal–organic frameworks: a review.* Energy Fuel 2022;36(6):2927–44.

[182] Kumaravelu TA, Jayapalan RR, Chang H-W, Kandasami A, Vayssieres L, Dong C-L. *Energy storage chemistry: Atomic and electronic fundamental understanding insights for high-performance supercapacitors.* Appl Phys Rev 2024;11(3).

[183] Wang T, Chen HC, Yu F, Zhao X, Wang H. *Boosting the cycling stability of transition metal compounds-based supercapacitors.* Energy Storage Mater 2019;16:545–73.

[184] Ramulu B, Shaik JA, Mule AR, Yu JS. *Improved rate capability and energy density of high-mass hybrid supercapacitor realized through long-term cycling stability testing and selective electrode design.* Materials Science and Engineering: R: Reports 2024;160:100820.

[185] Zhang GC, Feng M, Li Q, Wang Z, Fang Z, Niu Z, et al. *High energy density in combination with high cycling stability in hybrid supercapacitors.* ACS Appl Mater Interfaces 2022;14(2):2674–82.

[186] Panda S, Deshmukh K, Pasha SK, Theerthagiri J, Manickam S, Choi MY. *MXene based emerging materials for supercapacitor applications: recent advances, challenges, and future perspectives.* Coord Chem Rev 2022;462:214518.

[187] Pathak I, Acharya D, Chhetri K, Lohani PC, Ko TH, Muthurasu A, et al. *Ti3C2Tx MXene integrated hollow carbon nanofibers with polypyrrole layers for MOF-derived freestanding electrodes of flexible asymmetric supercapacitors.* Chem Eng J 2023;469:143388.

[188] Liu J, Xia Q, Wang L, Hu Q, Shinde NM, Zhou A. *In Situ growth of Nanorod-shaped Ni, Co-MOF on Mo2CT x MXene Surface to Realize Enhanced Energy Storage for Supercapacitors.* ACS Appl Mater Interfaces 2024;16(37):49380–91.

[189] Wei Y, Luo W, Li X, Lin Z, Hou C, Ma M, et al. *PANI-MnO2 and Ti3C2Tx (MXene) as electrodes for high-performance flexible asymmetric supercapacitors.* Electrochim Acta 2022;406:139874.

[190] Saha P, Ali A, Nayem SA, Shaheen Shah S, Aziz MA, Saleh Ahammad A. *Vanadium-based cathodic materials of aqueous zn-ion battery for superior-performance with prolonged-life cycle.* Chem Rec 2024;24(1):e202200310.

[191] Tajik S, Beitollahi H, Nejad FG, Kirlikovali KO, Van Le Q, Jang HW, et al. *Recent electrochemical applications of metal–organic framework-based materials.* Cryst Growth Des 2020;20(10):7034–64.

[192] Zhan F, Liu S, He Q, Zhao X, Wang H, Han M, et al. *Metal–organic framework-derived heteroatom-doped nanoarchitectures for electrochemical energy storage: recent advances and future perspectives.* Energy Storage Mater 2022;52:685–735.

[193] Jain M, Joshi B, Poddar P. *Poly (N-vinylpyrrolidone)-Assisted Crystal growth of Zeolitic Imidazolate Framework (ZIF-67) and Electrochemical Properties of its Derivatives for Flexible Supercapacitors.* Cryst Growth Des 2024;24(8):3179–94.

[194] Guo H, Zhang J, Xu M, Wang M, Yang F, Wu N, et al. *Zeolite-imidazole framework derived nickel-cobalt hydroxide on ultrathin MXene nanosheets for long life and high performance supercapacitance.* J Alloy Compd 2021;888:161250.

[195] Zheng J, Pan X, Huang X, Xiong D, Shang Y, Li X, et al. *Integrated NiCo2-LDHs@ MXene/rGO aerogel: componential and structural engineering towards enhanced performance stability of hybrid supercapacitor.* Chem Eng J 2020;396:125197.

[196] Olatoye AG, Li W, Fagbohun EO, Zeng X, Zheng Y, Cui Y. *High-performance asymmetric supercapacitor based on nickel-MOF anchored MXene//NPC/rGO.* J Electroanal Chem 2023;928:117036.

[197] Li C, Wang S, Cui Y, Wang X, Yong Z, Liang D, et al. *Sandwich-like MXene/α-Fe2O3–C–MoS2-PEDOT: PSS/MXene film electrodes with ultrahigh area capacitance for flexible supercapacitors.* ACS Appl Mater Interfaces 2022;14(7):9172–82.

[198] Li Y, Kamdem P, Jin X-J. *A freeze-and-thaw-assisted approach to fabricate MXene/ZIF-8 composites for high-performance supercapacitors and methylene blue adsorption.* J Electrochem Soc 2020;167(11):110562.

[199] Dharmasiri B, Usman KAS, Qin SA, Razal JM, Tran NT, Coia P, et al. *Ti3C2Tx MXene coated carbon fibre electrodes for high performance structural supercapacitors.* Chem Eng J 2023;476:146739.

[200] Nivetha R, Sharma S, Jana J, Chung JS, Choi WM, Hur SH. *Recent advances and New challenges: Two-Dimensional Metal–Organic Framework and their Composites/Derivatives for Electrochemical Energy Conversion and Storage.* Int J Energy Res 2023;2023(1):8711034.

[201] Luo Y, Yang C, Tian Y, Tang Y, Yin X, Que W. *A long cycle life asymmetric supercapacitor based on advanced nickel-sulfide/titanium carbide (MXene) nanohybrid and MXene electrodes.* J Power Sources 2020;450:227694.

[202] Ferrari S, Falco M, Muñoz-García AB, Bonomo M, Brutti S, Pavone M, et al. *Solid-state post Li metal ion batteries: a sustainable forthcoming reality?* Adv Energy Mater 2021;11(43):2100785.

[203] Pahari D, Verma P, Puravankara S. *Are Na-ion batteries nearing the energy storage tipping point?–current status of non-aqueous, aqueous, and solid-sate Na-ion battery technologies for sustainable energy storage.* J Storage Mater 2022;56:105961.

[204] Mallick S, Raj CR. *Aqueous Rechargeable Zn-ion Batteries: strategies for improving the Energy Storage Performance.* ChemSusChem 2021;14(9):1987–2022.

[205] Aslam MK, Wang H, Chen S, Li Q, Duan J. *Progress and perspectives of metal (Li, Na, Al, Zn and K)–CO2 batteries.* Mater Today Energy 2023;31:101196.

[206] Xu Z, Wang J. *Toward emerging sodium-based energy storage technologies: from performance to sustainability.* Adv Energy Mater 2022;12(29):2201692.

[207] Wu Y, Huang X, Huang L, Chen J. *Strategies for rational design of high-power lithium-ion batteries.* Energy & Environmental Materials 2021;4(1):19–45.

[208] Liu G, Wan W, Nie Q, Zhang C, Chen X, Lin W, et al. *Controllable long-term lithium replenishment for enhancing energy density and cycle life of lithium-ion batteries.* Energ Environ Sci 2024;17(3):1163–74.

[209] Zong H, Hu L, Wang Z, Qi R, Yu K, Zhu Z. *Metal-organic frameworks-derived CoP anchored on MXene toward an efficient bifunctional electrode with enhanced lithium storage.* Chem Eng J 2021;416:129102.

[210] Chen Y, Cheng J, Wang A, Liu C, Yan H, Qiu Y, et al. *The enhanced performance of Li-ion batteries based on Co-MOF/MXene composites.* Inorg Chem Commun 2024;159:111793.

[211] Bibi S, Shah SSA, Nazir MA, Helal MH, El-Bahy SM, El-Bahy ZM, et al. *MOF/MXene composites: synthesis, application and future perspectives.* Adv Sustainable Syst 2024;8(8):2400011.

[212] Zhang Q, Xu D, Si Y, Xu R, Luo B, He S, et al. *Ti3C2T X MXene Nanosheets decorated with magnetic Co Nanoparticles and CoO Nanosheets for Microwave Absorption.* ACS Appl Nano Mater 2022;5(5):7175–86.

[213] Gong W, Li SQ, Gao F, Lin J, Ye Y, Yang XR, et al. *Tailoring composites via in situ growth of Co-MOF on V2CTx MXene as high-performance anode for lithium-ion batteries.* Solid State Ion 2023;399:116295.

[214] Zhang Z, Guo H, Li W, Liu G, Zhang Y, Wang Y. *Sandwich-like Co 3 O 4/MXene composites as high capacity electrodes for lithium-ion batteries.* New J Chem 2020;44(15):5913–20.

[215] Yao L, Gu Q, Yu X. *Three-dimensional MOFs@ MXene aerogel composite derived MXene threaded hollow carbon confined CoS nanoparticles toward advanced alkali-ion batteries.* ACS Nano 2021;15(2):3228–40.

[216] Chen, K., H.n. Guo, W.q. Li, and Y.j. Wang, *MOF-derived core-shell CoP@ NC@ TiO2 composite as a high-performance anode material for Li-ion batteries.* Chemistry–An Asian Journal, 2021. **16**(4): p. 322-328.
[217] Dong Y, Lu P, Ding Y, Shi H, Feng X, Wu ZS. *Advanced design of cathodes and interlayers for high-performance lithium-selenium batteries.* SusMat 2021;1(3): 393–412.
[218] Vallem S, Song S, Oh Y, Kim J, Li M, Li Y, et al. *Designing a Se-intercalated MOF/MXene-derived nanoarchitecture for advancing the performance and durability of lithium-selenium batteries.* J Colloid Interface Sci 2024;665:1017–28.
[219] Li Y, Vallem S, Bae J. *MXene-based composites for high-performance and fire-safe lithium-ion battery.* Curr Appl Phys 2023;53:142–64.
[220] Wang Y, Song J, Wong WY. *Constructing 2D sandwich-like MOF/MXene heterostructures for durable and fast aqueous zinc-ion batteries.* Angew Chem 2023;135(8): e202218343.
[221] Lu H, Hu J, Zhang K, Zhao J, Deng S, Li Y, et al. *Microfluidic-Assisted 3D Printing Zinc Powder Anode with 2D Conductive MOF/MXene Heterostructures for High-Stable Zinc− Organic Battery.* Adv Mater 2024;36(6):2309753.
[222] Wang J, Zhang Y, Chen Z, Zhou Z, Wang J, Ma C, et al. *0D–2D multifunctional bimetallic MOF derivative-MXene heterojunction for high areal capacity lithium-sulfur batteries.* J Colloid Interface Sci 2025;678:79–88.
[223] Ming F, Liang H, Huang G, Bayhan Z, Alshareef HN. *MXenes for rechargeable batteries beyond the lithium-ion.* Adv Mater 2021;33(1):2004039.
[224] Tang M, Sun H, Su L, Gao Y, Chen F, Wang Z, et al. *Organics-MXene composites as electrode materials for energy storage.* Batteries Supercaps 2023;6(1): e202200402.
[225] Ashraf S, Abrar A, Alam MM, Al Nasir MH, Rehman MU, Zafar J, et al. *Surface Engineering of MXene-Based Materials for Next-Generation Rechargeable Batteries.* Metall Mater Eng 2025;31(1):541–65.
[226] Jayaramulu K, Devi B. *Hybrid two-dimensional porous materials.* Chem Mater 2023;35(22):9473–92.
[227] Nasrin K, Sudharshan V, Arunkumar M, Sathish M. *2D/2D nanoarchitectured Nb2C/Ti3C2 MXene heterointerface for high-energy supercapacitors with sustainable life cycle.* ACS Appl Mater Interfaces 2022;14(18):21038–49.
[228] Lei S-Y, Feng J-X, Chen Y-C, Zheng D, Liu W-X, Shi W-H, et al. *Advance in reversible Zn anodes promoted by 2D materials.* Rare Met 2024;43(4):1350–69.
[229] Wu L, Li W, Yin Y, Liu Z, Zheng B, Zhang Q, et al. *In-situ construction of Ti3C2TX/Ni-HHTP heterostructure as anode for lithium-ion batteries.* Mater Today Commun 2024;38:108160.
[230] Adil M, Olabi AG, Abdelkareem MA, Alawadhi H, Bahaa A, ElSaid K, et al. *In-situ grown bimetallic FeCu MOF-MXene composite for solid-state asymmetric supercapacitors.* J Storage Mater 2023;68:107817.
[231] Jakhar S, Singh N, Siwal SS. *In-situ synthesis of reduced graphene oxide templated MIL-53 (Fe) nanorods for photo-catalytic degradation of organic dyes under sunlight.* Vietnam Journal of Chemistry 2023;61(5):646–54.
[232] Liu C, Bai Y, Li W, Yang F, Zhang G, Pang H. *In situ growth of three-dimensional MXene/metal–organic framework composites for high-performance supercapacitors.* Angew Chem Int Ed 2022;61(11):e202116282.
[233] Safarkhani M, Aldhaher A, Lima EC, Zargar M, Jung EE, Huh Y, et al. *Engineering MXene@ MOF composites for a wide range of applications: a perspective.* ACS Appl Eng Mater 2023;1(11):3080–98.
[234] Thakur KK, Sharma AL, Singh S. *Exploring MXene-MOF composite for supercapacitor application.* Mater Chem Phys 2024;322:129463.
[235] Gao X, Zheng Y, Chang J, Xu H, Hui Z, Dai H, et al. *Universal strategy for preparing highly stable PBA/Ti3C2T x MXene toward lithium-ion batteries via chemical transformation.* ACS Appl Mater Interfaces 2022;14(13):15298–306.
[236] Zhuang X, Zhang S, Tang Y, Yu F, Li Z, Pang H. *Recent progress of MOF/MXene-based composites: Synthesis, functionality and application.* Coord Chem Rev 2023; 490:215208.
[237] Long Y, Wu Z, Tao Y, Yang QH. *Assembling of MXenes from liquid to Solid, Including Liquid Crystals, Fibers.* Transition Metal Carbides and Nitrides (MXenes) Handbook: Synthesis, Processing, Properties and Applications 2024:315–84.
[238] Zheng S, Zhou K, Zhang X, Ren N. *Metal–organic framework/MXene-based materials: preparations and applications.* RSC Adv 2025;15(37):30921.
[239] Pang W, Shao B, Tan X-Q, Tang C, Zhang Z, Huang J. *Exfoliation of metal–organic frameworks into efficient single-layer metal–organic nanosheet electrocatalysts by the synergistic action of host–guest interactions and sonication.* Nanoscale 2020;12(6):3623–9.
[240] Qin J, Liu B, Lam K-H, Song S, Li X, Hu X. *0D/2D MXene quantum dot/Ni-MOF ultrathin nanosheets for enhanced N2 photoreduction.* ACS Sustain Chem Eng 2020;8 (48):17791–9.
[241] Qu Y, Shi C, Cao H, Wang Y. *Synthesis of Ni-MOF/Ti3C2Tx hybrid nanosheets via ultrasonific method for supercapacitor electrodes.* Mater Lett 2020;280:128526.
[242] Li C, Wei H, Hua R, He X, Lu J, Chen Q, et al. *3D Cu-BTC anchored on 2D MXene nanosheets using surface control approach for urea adsorption to achieve the regeneration of dialysate.* Sep Purif Technol 2025:133594.
[243] Sharma A, Lee H-S, Yeom C-M, Surendran HK, Narayana C, Eadi SB, et al. *Tailoring conductive MXene@ MOF interfaces: new generation of synapse devices for neuromorphic computing.* Chem Mater 2024;36(17):8466–76.
[244] Ramasundaram S, Jeevanandham S, Vijay N, Divya S, Jerome P, Oh TH. *Unraveling the Dynamic Properties of New-Age Energy Materials Chemistry using Advanced In Situ Transmission Electron Microscopy.* Molecules 2024;29(18):4411.
[245] Aldhaher A, Rabiee N, Iravani S. *Exploring the synergistic potential of MXene-MOF hybrid composites: a perspective on synthesis, properties, and applications.* Hybrid Adv 2024;5:100131.
[246] Patial SK, Sharma A, Singh S. *Synthesis and Fabrication Techniques of MXene.* In: *Surface Engineering of MXenes.* Springer; 2025. p. 37–72.
[247] Bandpey M, Barz DP. *Effects of interlayer space engineering and surface modification on the charge storage mechanisms of MXene nanomaterials: a review on recent developments.* Nanoscale 2024.
[248] Chen C, Shen L, Wang B, Lu X, Raza S, Xu J, et al. *Environmental applications of metal–organic framework-based three-dimensional macrostructures: a review.* Chem Soc Rev 2025.
[249] Jung S, Zafar U, Achary LSK, Koo CM. *Ligand chemistry for surface functionalization in MXenes: a review.* EcoMat 2023;5(10):e12395.
[250] Zorainy MY, Alalm MG, Kaliaguine S, Boffito DC. *Revisiting the MIL-101 metal–organic framework: design, synthesis, modifications, advances, and recent applications.* J Mater Chem A 2021;9(39):22159–217.
[251] Panahi-Sarmad M, Guo T, Hashemi SA, Ghaffarkhah A, Wuttke S, Arjmand M, et al. *Hierarchically MOF-Based Porous Monolith Composites for Atmospheric Water Harvesting.* Adv Mater 2025:2413353.
[252] Hui X, Ge X, Zhao R, Li Z, Yin L. *Interface chemistry on MXene-based materials for enhanced energy storage and conversion performance.* Adv Funct Mater 2020;30 (50):2005190.
[253] Goyal N, Li F, Hu Y-B. *Tailoring single-metal atom catalysts: a strategic defect engineering approach for electrochemical reduction reactions.* J Mater Chem A 2024;12 (31):19685–719.
[254] Yang X-Y, Chen L-H, Li Y, Rooke JC, Sanchez C, Su B-L. *Hierarchically porous materials: synthesis strategies and structure design.* Chem Soc Rev 2017;46(2): 481–558.
[255] Chen C, Yang R, Zhu J, Yao W, Tang Y. *Superior sodium metal anodes enabled by 3D hierarchical metallic scaffolds with enhanced sodiophilicity.* Adv Sci 2025: 2500756.
[256] Islam N, Das M, Johan BA, Shah SS, Alzahrani AS, Aziz MA. *Multifunctional Screen-Printed Conductive Inks: Design Principles, Performance challenges, and Application Horizons.* ACS Appl Electron Mater 2025;7(16):7503–44.
[257] Kitchamsetti N, Cho JS. *A roadmap of recent advances in MXene@ MOF hybrids, its derived composites: Synthesis, properties, and their utilization as an electrode for supercapacitors, rechargeable batteries and electrocatalysis.* J Storage Mater 2024;80:110293.
[258] Wu F, Liu Z, Wang J, Shah T, Liu P, Zhang Q, et al. *Template-free self-assembly of MXene and CoNi-bimetal MOF into intertwined one-dimensional heterostructure and its microwave absorbing properties.* Chem Eng J 2021;422:130591.
[259] Nahirniak S, Ray A, Saruhan B. *Challenges and future prospects of the MXene-based materials for energy storage applications.* Batteries 2023;9(2):126.

[260] Ampong DN, Agyekum E, Agyemang FO, Mensah-Darkwa K, Andrews A, Kumar A, et al. *MXene: fundamentals to applications in electrochemical energy storage*. Discover Nano 2023;18(1):3.
[261] Liu Y, Zhou H, Zhou W, Meng S, Qi C, Liu Z, et al. *Biocompatible, high-performance, wet-adhesive, stretchable all-hydrogel supercapacitor implant based on PANI@ rGO/Mxenes electrode and hydrogel electrolyte*. Adv Energy Mater 2021;11(30):2101329.
[262] Palanisamy S, Gopalakrishnan M, Ingavale S, Etesami M, Limphirat W, Liu W-R, et al. *Sandwiched heterostructure of NiFe2O4/TiO2 nanocrystals and MXene nanosheets for highly active oxygen electrocatalyst in rechargeable zinc-air batteries*. J Storage Mater 2024;98:113139.
[263] Ramachandran T, Hamed F, Kumar YA, Raji RK, Hegazy H. *Multifunctional covalent-organic frameworks (COFs)-2D MXenes composites for diverse applications*. J Storage Mater 2023;73:109299.
[264] Mousavi SR, Hosseini H. *Metal–organic frameworks/MXenes hybrid nanomaterials for energy storage applications*. J Mater Sci Mater Electron 2023;34(9):818.
[265] Mane RS, Mane S, Somkuwar V, Thombre NV, Patwardhan AV, Jha N. *A novel hierarchically hybrid structure of MXene and bi-ligand ZIF-67 based trifunctional electrocatalyst for zinc-air battery and water splitting*. Battery Energy 2023;2(5):20230019.
[266] Phung J, Zhang X, Deng W, Li G. *An overview of MOF-based separators for lithium-sulfur batteries*. Sustain Mater Technol 2022;31:e00374.
[267] Li YX, Feng YS, Li LX, Yin X, Cao FF, Ye H. *Green synthesis and applications of MXene for lithium–sulfur batteries*. Energy Storage Mater 2024;67:103257.
[268] Cui Y, Zhou X, Huang X, Xu L, Tang S. *Binary transition-metal sulfides/MXene synergistically promote polysulfide adsorption and conversion in lithium–sulfur batteries*. ACS Appl Mater Interfaces 2023;15(42):49223–32.
[269] Liu F, Wang T, Liu X, Jiang N, Fan L-Z. *High-performance heterojunction Ti3C2/CoSe2 with both intercalation and conversion storage mechanisms for magnesium batteries*. Chem Eng J 2021;426:130747.
[270] Mahajan P. *Fundamentals to applications of MXenes for biosensing*. J Electrochem Soc 2024;171(2):027516.
[271] Iravani S, Zare EN, Zarrabi A, Khosravi A, Makvandi P. *MXene/zeolitic imidazolate framework (ZIF) composites: a perspective on their emerging applications*. FlatChem 2024;44:100631.
[272] Dai Y, Sun C, Gul H, Tan L, Guo Y, Qiu D, et al. *Three-dimensional honeycomb composites consist of metal carbides and layered double hydroxides for high-performance supercapacitor electrode materials*. J Power Sources 2024;602:234306.
[273] Zhang H, Feng S, Li X, Chen X, Chen L, Xiao J. *Porous structure of fixed sulfur and networked electronic channels in three-dimensional skeletal structure of polyaniline and MOF-derived materials*. Colloids Surf A Physicochem Eng Asp 2023;669:131440.
[274] Alli YA, Bamisaye A, Nancy P, Zachariah SM, Oladoye PO, Bankole OM, et al. *MXene composites: Properties, synthesis and its emerging application in rechargeable batteries*. J Storage Mater 2024;77:109954.
[275] Lokhande P, Kulkarni S, Chakrabarti S, Pathan H, Sindhu M, Kumar D, et al. *The progress and roadmap of metal–organic frameworks for high-performance supercapacitors*. Coord Chem Rev 2022;473:214771.
[276] Parker T, Zhang D, Bugallo D, Shevchuk K, Downes M, Valurouthu G, et al. *Fourier-transform infrared spectral library of MXenes*. Chem Mater 2024;36(17):8437–46.
[277] Hao LP, Hanan A, Walvekar R, Khalid M, Bibi F, Wong WY, et al. *Synergistic integration of MXene and metal-organic frameworks for enhanced electrocatalytic hydrogen evolution in an alkaline environment*. Catalysts 2023;13(5):802.
[278] Shingte S, Chavan V, Dhavale R, Kim D-K, Park H-H, Dongale T, et al. *Optimizing supercapacitive performance of MXene through MOF-derived nickel ferrite nanoparticle integration*. J Storage Mater 2024;92:112169.
[279] Liu Y, He Y, Vargun E, Plachy T, Saha P, Cheng Q. *3D porous Ti_3C_2 MXene/NiCo-MOF composites for enhanced lithium storage*. Nanomaterials 2020;10(4):695.
[280] Ma Z, Zhou X, Deng W, Lei D, Liu Z. *3D porous MXene (Ti3C2)/reduced graphene oxide hybrid films for advanced lithium storage*. ACS Appl Mater Interfaces 2018;10(4):3634–43.
[281] Ma G, Zhou X, Cao Y, Guan X, Wu W, Zhang S, et al. *Sulfonated polyaniline coated Prussian blue analog derived Mn-Fe oxide composite electrode for all-solid-state flexible supercapacitors*. Chem Eng J 2025;508:160942.
[282] Liang Y, Guo J, Zhang H, Brett DJ, Gadipelli S. *Superior supercapacitor performance with tuneable 2D/3D morphological microporous carbons of zeolitic imidazolate frameworks synthesized by recycling mother liquors*. Chem Eng J 2024;489:151190.
[283] Cao F, Zhang Y, Wang H, Khan K, Tareen AK, Qian W, et al. *Recent advances in oxidation stable chemistry of 2D MXenes*. Adv Mater 2022;34(13):2107554.
[284] Lohita, B. and M. Srijaya, *Novel technologies for shelf-life extension of food products as a competitive advantage: A review.* Food production, diversity, and safety under climate change, 2024: p. 285-306.
[285] Liu F, Fan Z. *Defect engineering of two-dimensional materials for advanced energy conversion and storage*. Chem Soc Rev 2023;52(5):1723–72.
[286] Liang L, Zhang W, Zhao F, Denis DK, Zaman FU, Hou L, et al. *Surface/interface structure degradation of Ni-rich layered oxide cathodes toward lithium-ion batteries: fundamental mechanisms and remedying strategies*. Adv Mater Interfaces 2020;7(3):1901749.
[287] Zhang L, Chen S, You Z. *Hybrid cross-linking to construct functional elastomers*. Acc Chem Res 2023;56(21):2907–20.
[288] Zheng C, Yao Y, Rui X, Feng Y, Yang D, Pan H, et al. *Functional MXene-based materials for next-generation rechargeable batteries*. Adv Mater 2022;34(51):2204988.
[289] Xu G, Zhu C, Gao G. *Recent progress of advanced conductive metal–organic frameworks: precise synthesis, electrochemical energy storage applications, and future challenges*. Small 2022;18(44):2203140.
[290] Hachhach M, Bayou S, El Kasmi A, Saidi MZ, Akram H, Hanafi M, et al. *Towards Sustainable Scaling-up of Nanomaterials Fabrication: Current Situation, challenges, and Future Perspectives*. Eng 2025;6(7):149.
[291] Alkhadra MA, Su X, Suss ME, Tian H, Guyes EN, Shocron AN, et al. *Electrochemical methods for water purification, ion separations, and energy conversion*. Chem Rev 2022;122(16):13547–635.
[292] Xiong F, Hu H, Xue X, Wu M, Zhou J, Zhang W, et al. *Sandwich-structured continuous ZIF-8/Ti3C2 MXene/ZIF-8 for efficient sterilization: Enhanced photocatalytic activity, photothermal effect, and environmental safety*. Water Res 2024;259:121888.
[293] Ranjith KS, Ghoreishian SM, Han S, Chodankar NR, Raju GSR, Marje SJ, et al. *Synergistic effects of layered Ti3C2TX MXene/MIL-101 (Cr) heterostructure as a sonocatalyst for efficient degradation of sulfadiazine and acetaminophen in water*. Ultrason Sonochem 2023;99:106570.
[294] Far HS, Najafi M, Moradi E, Atighi M, Rabbani M, Hasanzadeh M. *Metal-organic frameworks decorated Ti3C2Tx MXene nanosheets (MXene@ UiO-66) for enhanced photocatalytic dye degradation*. J Mol Struct 2024;1312:138627.
[295] Albargi HB, Zeeshan M, Iqbal M, Sunny MA, Ahmad J, Diab M, et al. *Advanced hierarchical MIL-53/Ti3C2@ MnO2 composites for superior supercapattery performance and efficient hydrogen evolution reaction*. Diam Relat Mater 2025;156:112409.