

Performance Evaluation of MXene-Based Nanocomposites for Advanced Energy Storage

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ABSTRACT

The escalating global demand for high-performance energy storage systems has catalyzed intensive research into two-dimensional (2D) nanomaterials that bridge the performance gap between conventional batteries and supercapacitors. Among emerging 2D materials, MXenes — a family of transition metal carbides, nitrides, and carbonitrides — have distinguished themselves through exceptional metallic conductivity, hydrophilic surface chemistry, and tunable interlayer spacing. This comprehensive review evaluates the performance characteristics of MXene-based nanocomposites across supercapacitor, lithium-ion battery, sodium-ion battery, and zinc-ion hybrid capacitor applications. The study systematically examines synthesis methodologies including hydrofluoric acid etching, minimally invasive layer delamination (MILD), molten salt synthesis, and emerging HF-free routes. Performance metrics encompassing specific capacitance, energy density, power density, cycling stability, and rate capability are critically analyzed for MXene/carbon, MXene/conductive polymer, MXene/metal oxide, MXene/metal sulfide, MXene/layered double hydroxide, and MXene/metal-organic framework composites. The analysis reveals that $\text{Ti}_3\text{C}_2\text{T}_x$ -based composites achieve specific capacitances exceeding 1500 F g^{-1} when hybridized with layered double hydroxides, while MXene/conductive polymer composites demonstrate superior energy densities up to 50.6 Wh L^{-1} . Critical challenges including MXene oxidation susceptibility, restacking phenomena, and scalability constraints are identified. Future research directions emphasize high-entropy MXenes, 3D architected electrodes, and smart responsive coatings for next-generation energy storage. This review consolidates recent advances and provides a roadmap for rational design of MXene nanocomposites with optimized electrochemical performance.

Keywords: MXene, nanocomposite, energy storage, supercapacitor, lithium-ion battery, electrochemical performance, $\text{Ti}_3\text{C}_2\text{T}_x$, pseudocapacitance

INTRODUCTION

The twenty-first century has witnessed an unprecedented surge in energy consumption driven by rapid urbanization, electrification of transportation, and proliferation of portable electronic devices. The International Energy Agency projects that global electricity demand will increase by approximately 60% by 2040, necessitating revolutionary advancements in energy storage technologies [1]. Current energy storage paradigms are dominated by lithium-ion batteries (LIBs) and electrical double-layer capacitors (EDLCs), each presenting inherent limitations. LIBs offer high energy densities ($150\text{--}250 \text{ Wh kg}^{-1}$) but suffer from modest power densities, limited cycle life (typically 500–2000 cycles), and safety concerns arising from dendritic lithium growth [2]. Conversely, supercapacitors deliver exceptional power densities ($>10 \text{ kW kg}^{-1}$) and

extended cycle stability ($>100,000$ cycles) but are constrained by low energy densities ($<10 \text{ Wh kg}^{-1}$) that impede widespread adoption in electric vehicles and grid-scale storage [3].

This performance dichotomy has stimulated vigorous research into pseudocapacitive materials and nanostructured electrodes that can simultaneously achieve battery-level energy density and capacitor-level power density. Two-dimensional nanomaterials, particularly graphene, transition metal dichalcogenides, and MXenes, have emerged as promising candidates owing to their unique electronic structures, high surface-to-volume ratios, and facile ion transport pathways [4].

Discovery and Evolution of MXenes

MXenes were first discovered in 2011 by researchers at Drexel University who demonstrated the selective etching of aluminum layers from Ti_3AlC_2 MAX phases using hydrofluoric acid, yielding two-dimensional Ti_3C_2 sheets [5]. The general chemical formula of MXenes is $\text{M}_{n+1}\text{X}_n\text{T}_x$, where M represents an early transition metal (Ti, V, Nb, Mo, etc.), X denotes carbon and/or nitrogen, n varies from 1 to 4, and T_x signifies surface terminations (-O, -OH, -F, -Cl) introduced during synthesis [6]. To date, over 30 stoichiometric MXene compositions have been experimentally synthesized, with theoretical predictions suggesting the existence of more than 100 stable configurations [7].

The distinctive attributes of MXenes that render them exceptional for energy storage include: (i) metallic conductivity comparable to multilayer graphene (up to 8000 S cm^{-1} for $\text{Ti}_3\text{C}_2\text{T}_x$); (ii) hydrophilic surfaces arising from polar terminal groups that facilitate electrolyte wetting; (iii) tunable interlayer spacing (0.6–2.0 nm) that accommodates ion intercalation; and (iv) pseudocapacitive charge storage mechanisms involving reversible redox reactions of transition metal centers [8,9]. These characteristics position MXenes as versatile platforms for constructing high-performance composite electrodes.

Scope and Objectives

This review presents a systematic performance evaluation of MXene-based nanocomposites for advanced energy storage applications. The specific objectives are:

To comprehensively review synthesis methodologies and their influence on MXene quality, yield, and surface chemistry

To evaluate the electrochemical performance of MXene nanocomposites across diverse energy storage architectures

To establish performance benchmarks and comparative metrics for rational composite design

To identify critical challenges including oxidation stability, restacking, and scalability

To delineate future research trajectories toward commercial viability

The scope encompasses supercapacitors (EDLCs, pseudocapacitors, hybrid devices), lithium-ion batteries, sodium-ion batteries, zinc-ion hybrid capacitors, and emerging flexible/wearable energy storage systems.

SYNTHESIS AND STRUCTURAL CHARACTERISTICS OF MXenes

Synthesis Approaches

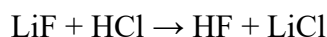
General synthesis approaches of MXenes are Hydrofluoric Acid Etching, Minimally Invasive Layer Delamination (MILD), Molten Salt Etching, and Electrochemical Etching.

Hydrofluoric Acid Etching: The conventional HF etching method involves immersing MAX phase powders in concentrated HF (typically 40–50 wt%) at room temperature for 24–48 hours. The fluoride ions selectively attack the M–A metallic bonds, extracting the A-layer element (typically Al) while preserving the M–X

covalent framework [5,11]. The resulting multilayer MXene (m-MXene) requires subsequent delamination via sonication in organic solvents or intercalation with molecules such as tetrabutylammonium hydroxide (TBAOH) to yield single- or few-layer flakes.

While HF etching produces high-quality MXenes with well-defined surface terminations, the method presents severe safety hazards and environmental concerns associated with concentrated hydrofluoric acid. Furthermore, the harsh chemical environment introduces defects and reduces flake dimensions, potentially compromising mechanical integrity [11].

Minimally Invasive Layer Delamination (MILD): The MILD method, developed by Gogotsi and colleagues, employs a mixture of lithium fluoride (LiF) and hydrochloric acid (HCl) as an in-situ HF source [9,11]. The LiF–HCl system generates HF gradually through the reaction:



This controlled HF release enables gentler etching kinetics that preserve larger flake sizes, enhance yield (>90%), and produce MXenes with predominantly –O and –OH terminations rather than –F groups. The MILD method has become the most widely adopted synthesis protocol owing to its improved safety profile, scalability, and superior electrochemical performance of the resulting MXenes [11].

Molten Salt Etching: Molten salt etching represents an HF-free alternative that utilizes Lewis acidic salts (ZnCl₂, CuCl₂, FeCl₃) at elevated temperatures (500–800°C) to selectively extract A-layer elements [15]. This approach enables the synthesis of MXenes with unconventional compositions including Cl-terminated and Br-terminated surfaces that are inaccessible through fluoride-based methods. However, the high-temperature processing introduces challenges in controlling flake thickness and surface uniformity, and the energy-intensive nature of molten salt synthesis raises scalability concerns.

Electrochemical Etching: Electrochemical methods apply controlled anodic potentials to MAX phase electrodes immersed in mild electrolytes, achieving selective A-layer removal without hazardous fluorides. The electrochemical approach offers precise control over etching kinetics through potential modulation and produces MXenes with minimal structural defects. Nevertheless, the method remains primarily a laboratory-scale technique with limited throughput, and the requirement for conductive MAX phase electrodes constrains material selection.

Alternative Synthesis Routes

Alternative synthesis routes include Chemical Vapor Deposition (CVD) and hydrothermal and solvothermal methods.

Chemical Vapor Deposition: CVD-based synthesis of MXenes from metal halide and methane precursors has been proposed for the growth of ultrathin, large-area MXene films on substrates such as sapphire and copper foil. While CVD would enable precise thickness control and epitaxial growth, the high processing temperatures (>1000°C) and complex precursor chemistry currently limit this approach to fundamental studies rather than scalable production.

Hydrothermal and Solvothermal Methods: Hydrothermal synthesis facilitates the preparation of MXene-based composites through in-situ growth of secondary phases on MXene substrates. The high-pressure, high-temperature aqueous environment promotes crystallization of metal oxides, sulfides, and hydroxides while maintaining MXene structural integrity. Solvothermal methods employing organic solvents extend the range of accessible composite morphologies through controlled dielectric environments.

Surface Chemistry and Termination Effects

The surface terminations of MXenes profoundly influence their electrochemical behavior. Density functional theory (DFT) calculations indicate that –O terminated MXenes exhibit the highest work function and most favorable ion adsorption energetics, while –F terminations reduce electrical conductivity and impede ion

transport [18]. Experimental studies confirm that post-synthesis treatments including annealing in inert atmospheres, alkalization to remove $-F$ groups, and controlled oxidation can optimize surface chemistry for specific energy storage applications [14].

Figure 1 illustrates the schematic progression from MAX phase to delaminated MXene nanosheets through selective etching and delamination processes.

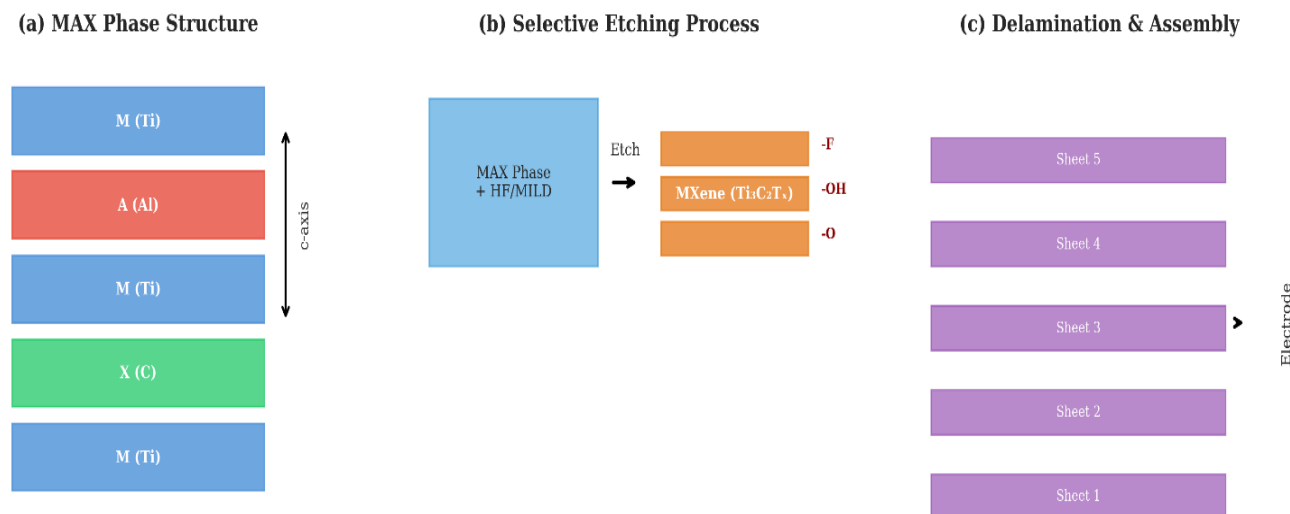


Figure 1. Schematic illustration of MXene synthesis: (a) layered MAX phase structure showing M, A, and X elements; (b) Selective etching process using HF or MILD methods with surface termination formation; (c) Delamination into individual MXene sheets and electrode assembly.

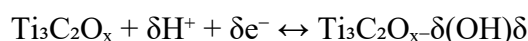
CHARGE STORAGE MECHANISMS IN MXENE ELECTRODES

a) Electric Double Layer Capacitance

The basal planes of MXene nanosheets provide extensive surfaces for electric double layer formation. The Helmholtz layer capacitance arises from electrostatic charge separation at the electrode–electrolyte interface, with contributions from both the external surfaces and internal galleries between stacked sheets [22]. The interlayer spacing of MXenes (typically 1.0–1.5 nm for delaminated films) is sufficiently large to accommodate hydrated ions (Li^+ : 0.38 nm; Na^+ : 0.36 nm; K^+ : 0.33 nm) while maintaining high volumetric charge storage [23].

b) Pseudocapacitance

Pseudocapacitive charge storage in MXenes involves fast, reversible redox reactions at transition metal centers without bulk phase transformation. For $Ti_3C_2T_x$, the primary redox couple involves Ti^{3+}/Ti^{4+} interconversion accompanied by proton or cation intercalation:



The pseudocapacitive contribution dominates in acidic electrolytes (particularly H_2SO_4) where proton intercalation occurs with minimal structural distortion, enabling capacitance values exceeding 300 F g^{-1} for pristine $Ti_3C_2T_x$ electrodes [24].

c) Ion Intercalation

In non-aqueous electrolytes and battery configurations, MXenes function as intercalation hosts where alkali metal ions (Li^+ , Na^+ , K^+) occupy interlayer galleries and vacant sites within the hexagonal close-packed structure. The intercalation mechanism provides battery-like capacity while maintaining the kinetics advantages of 2D materials [25]. The expansion of interlayer spacing through pillaring with carbon nanotubes,

graphene, or metal oxide nanoparticles enhances ion accessibility and reduces diffusion barriers.

Figure 2 presents the comparative electrochemical performance of various MXene-based nanocomposites, illustrating the relationship between specific capacitance, cycle life, and capacitance retention.

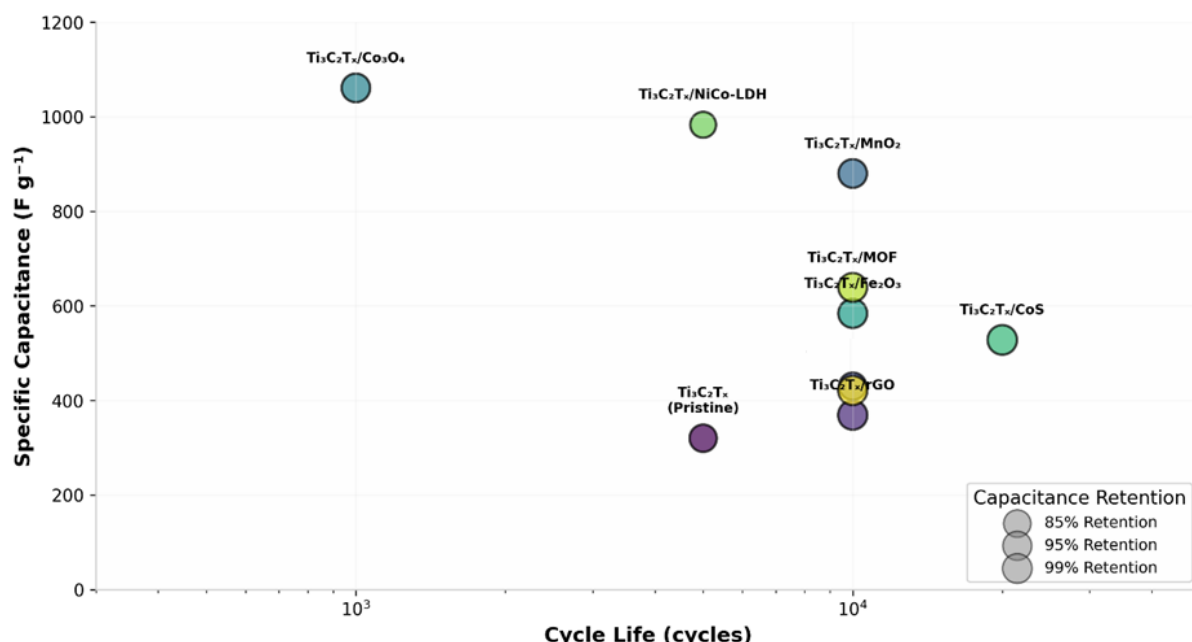


Figure 2. Comparative electrochemical performance of MXene-based nanocomposites. Bubble chart illustrating specific capacitance versus cycle life, where bubble size is proportional to capacitance retention percentage. Data compiled from recent literature (2022–2025).

MXENE-BASED NANOCOMPOSITES FOR SUPERCAPACITORS

a) MXene/Carbon Nanocomposites

The integration of carbon nanomaterials — including graphene, reduced graphene oxide (rGO), carbon nanotubes (CNTs), and activated carbon — with MXenes addresses the critical issue of nanosheet restacking while enhancing electrical conductivity and mechanical stability. The carbonaceous components function as spacers that maintain interlayer galleries for electrolyte penetration and ion transport [27,28,55].

Li et al. synthesized MXene/acidified activated carbon (AAC) composites through self-assembly, achieving an interlayer spacing of 109.8 nm that facilitated rapid ion diffusion. The composite electrode delivered a specific capacitance of 369 F g⁻¹ at 0.5 A g⁻¹ with exceptional 97.4% capacitance retention after 10,000 cycles [27]. Shao et al. prepared MXene/rGO composite aerogels via freeze-drying, obtaining free-standing electrodes with mechanical strength of 16.18 MPa and capacitance of 233 F g⁻¹ with 91% retention over 10,000 cycles [28].

Sutar et al. reported a Ti₃C₂T_x/TiO₂@GO nanocomposite synthesized through solid-state reduction, exhibiting remarkable cycling stability with 98.2% capacity retention after 50,000 cycles in acidic electrolyte and a specific capacitance of 930.8 F g⁻¹ [29]. The uniform GO coating protected MXene from oxidation while providing additional active sites for charge storage.

b) MXene/Conductive Polymer Composites

Conductive polymers — polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT) — offer high theoretical capacitances through reversible redox reactions and complement MXene's metallic conductivity. The synergistic combination yields composites with enhanced energy density while maintaining high power capability [30].

Varghese et al. compared MXene-PANI and MXene-PPy composites, finding that MXene-PANI electrodes outperformed MXene-PPy with specific capacitance of 430 F g^{-1} and energy density of 38 Wh kg^{-1} at 808 W kg^{-1} , compared to 305 F g^{-1} for the PPy counterpart. Both systems demonstrated $\sim 85\%$ retention after 10,000 galvanostatic charge-discharge cycles [31].

Chen et al. developed PANI/Ti₃C₂T_x composites via supramolecular self-assembly using DL-tartaric acid, achieving a high specific capacitance of 452 F g^{-1} with an expanded voltage window of 1.9 V. The TDP2 electrode (MXene:aniline = 2:8) exhibited enhanced electron/ion transfer facilitated by the supramolecular dopant [32]. Ma et al. designed flexible binder-free MXene supercapacitor electrodes through calcination-based integration of polymer carbonization, alkali treatment, and template sacrificing, achieving 532.9 F g^{-1} at 5 mV s^{-1} with 97.1% retention after 40,000 cycles [33].

c) MXene/Metal Oxide Composites

Transition metal oxides (TMOs) including MnO₂, Co₃O₄, Fe₂O₃, RuO₂, and MoO₃ provide high theoretical capacitances through multiple oxidation states but suffer from poor electrical conductivity and structural degradation during cycling. MXene matrices address these limitations by providing conductive scaffolds that accommodate volume expansion and enhance charge transfer kinetics [34].

Wu et al. synthesized MXene/MnO₂/Ag ternary composites achieving a specific capacitance of 880.8 F g^{-1} at 2 A g^{-1} with energy density of 39.9 Wh kg^{-1} at power density of 2955.8 W kg^{-1} [35]. Shen et al. reported Co₃O₄-coated Nb₂CT_x MXene forming a 2D cross-linked structure with maximum capacitance of 1061 F g^{-1} , substantially exceeding bulk Co₃O₄ and pristine Nb₂C electrodes [36]. The asymmetric device Co₃O₄/Nb₂C//AC delivered energy density of 60.3 Wh kg^{-1} at 670 W kg^{-1} with 93% retention over 1000 cycles.

Anakha et al. demonstrated β -cyclodextrin-stabilized CuO nanoparticles anchored on MXene nanosheets via wet impregnation, reporting 1693.43 F g^{-1} at 0.90 A g^{-1} with 86% retention after 10,000 cycles [37]. Moniruzzaman et al. constructed 3D-0D-2D ternary heterostructures (SnO₂/carbon dots@MXene) on nickel foam, exhibiting 1074 F g^{-1} in three-electrode configuration and 51.11 Wh kg^{-1} energy density in asymmetric devices with near 100% retention after 10,000 cycles [38].

d) MXene/Metal Sulfide and Selenide Composites

Metal sulfides (CoS, CoS₂, MoS₂, WS₂) and selenides (CoSe₂, NiCoSe₂) offer rich redox chemistry and high theoretical capacities. Their integration with MXenes leverages the conductive MXene network to overcome the intrinsically low conductivity of sulfide materials while the sulfide nanoparticles prevent MXene restacking [39].

Sharma et al. fabricated 1T-VS₂/MXene hybrids via hydrothermal synthesis, achieving specific capacitance of 115.7 F g^{-1} at 0.8 A g^{-1} and energy density of 41.13 Wh kg^{-1} . The CV analysis revealed 92.1% capacitive contribution from K⁺ intercalation/deintercalation into MXene layers combined with EDL-type pseudocapacitance from VS₂ [40]. Yan et al. grew FeCo₂S₄ on MXene in situ, achieving 2415.3 F g^{-1} with 90.5% retention; the asymmetric device delivered 68.7 Wh kg^{-1} at 800 W kg^{-1} [41].

Chaudhary et al. synthesized polymorphic Co_xSe_y integrated into 3D Ti₃C₂T_x/rGO foam, achieving 243.1 mAh g^{-1} at 1 A g^{-1} with 91.3% capacity retention after 5000 cycles [42]. Samal et al. constructed NiCoSe₂/Ti₃C₂T_x heterostructures with energy densities of 32.05 Wh kg^{-1} at 200 W kg^{-1} , attributed to synergistic electron transfer from MXene to NiCoSe₂ that increased density of states near the Fermi level [43].

e) MXene/Layered Double Hydroxide Composites

Layered double hydroxides (LDHs) — represented by the general formula $[\text{M}^{2+}_{1-x}\text{M}^{3+}_x(\text{OH})_2]^{x+}(\text{A}^{n-})_{x/n} \cdot y\text{H}_2\text{O}$ — provide exceptional pseudocapacitance through reversible redox reactions of transition metal cations. The combination with MXenes creates hierarchical heterostructures with accelerated electron transport and ion diffusion [44].

Zhang et al. anchored NiMn-LDH on Ti_3C_2 MXene via in situ crystallization, achieving 1575 F g^{-1} with 90% retention after 10,000 cycles. The lithium-ion capacitor assembled with this composite delivered 122.7 Wh kg^{-1} at 199 W kg^{-1} and retained 90.4% capacity after 10,000 cycles under an extended voltage window of 0.01–4.0 V [45]. Pan's research team synthesized $\text{V}_2\text{CT}_x/\text{NiV-LDH}$ composites via hydrothermal synthesis at 120°C , obtaining high specific surface area ($74.99 \text{ m}^2 \text{ g}^{-1}$) and asymmetric device energy density of 54.19 Wh kg^{-1} at 750 W kg^{-1} [46].

Jiang et al. designed CoNi-LDH@MXene-carbon nanofiber fibers through electrospinning and hydrolysis, achieving 996 F g^{-1} at 1 A g^{-1} with asymmetric supercapacitor energy density of 48.4 Wh kg^{-1} [47]. Zhang et al. constructed FeNi-LDH/ $\text{Ti}_3\text{C}_2\text{T}_x$ nanohybrids via ionic hetero-assembly, enabling symmetric supercapacitors to deliver 94.1 Wh kg^{-1} at 802.4 W kg^{-1} [48].

f) MXene/Metal-Organic Framework Composites

Metal-organic frameworks (MOFs) provide ultrahigh surface areas and tunable pore structures but generally exhibit poor electrical conductivity. MXene/MOF composites combine the porosity and redox activity of MOFs with the metallic conductivity of MXenes, yielding enhanced electrochemical performance [49].

Zhang et al. self-assembled Ni MOF amorphous nanospheres on $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets, subsequently converting them to porous nickel phosphates. The electrode achieved 639 C g^{-1} at 0.5 A g^{-1} with 85% retention after 10,000 cycles. [Note: The original value is reported in coulombs per gram (C g^{-1}), not farads per gram (F g^{-1}). Conversion to capacitance requires division by the operating voltage window.] The asymmetric device using PPD-rGO cathode delivered 72.6 Wh kg^{-1} at 932 W kg^{-1} with 94% retention [50]. Kshetri et al. developed flexible quasi-solid-state supercapacitors using Co-MOF on MXene-carbon nanofiber mats, achieving 426.7 F g^{-1} and hybrid device energy density of 72.5 Wh kg^{-1} with 90.36% retention after 10,000 cycles [51].

Figure 3 presents the Ragone plot comparing MXene-based energy storage devices with conventional battery and supercapacitor benchmarks.

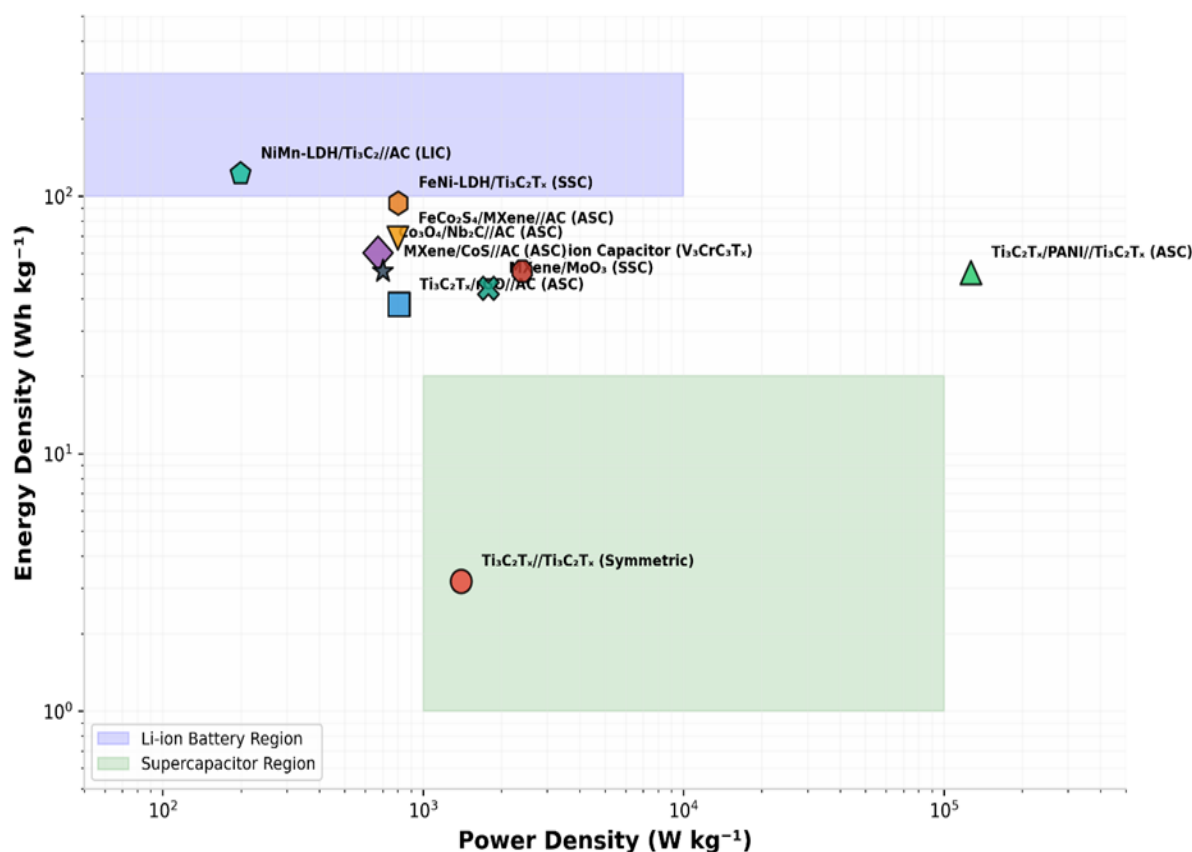


Figure 3. Ragone plot comparing energy density versus power density for various MXene-based energy storage devices. Shaded regions indicate typical performance ranges for lithium-ion batteries and conventional supercapacitors.

MXENE NANOCOMPOSITES FOR BATTERY APPLICATIONS

Lithium-Ion Batteries

MXenes have been extensively investigated as anode materials for LIBs owing to their low Li^+ diffusion barriers, high volumetric capacity, and ability to accommodate volume changes during lithiation/delithiation. The theoretical capacity of Ti_3C_2 for Li storage is approximately 320 mAh g^{-1} based on intercalation mechanisms, with experimental values often exceeding this due to additional surface adsorption and defect-mediated storage [52].

Guo et al. synthesized $\text{TiS}_2/\text{MXene}$ composites with various molar ratios, demonstrating enhanced rate capability attributed to the conductive MXene network facilitating electron transport to TiS_2 active sites [54]. The $\text{Ti}_3\text{C}_2\text{T}_x/\text{CNT}$ composite prevents restacking and facilitates electrolyte transport, achieving volumetric capacity of 421 mAh cm^{-3} at 20 mA g^{-1} with excellent cycling stability [55]. Sb/MXene hybrids prepared via HF etching delivered reversible capacity of 450 mAh g^{-1} at 0.1 A g^{-1} after 100 cycles, with the synthesis method significantly influencing electrochemical performance [56].

Sodium-Ion Batteries

Sodium-ion batteries represent a cost-effective alternative to LIBs for grid-scale storage, though the larger ionic radius of Na^+ ($1.02 \text{ \AA}$ vs $0.76 \text{ \AA}$ for Li^+) necessitates electrode materials with expanded interlayer spacing. MXenes with interlayer distances $>1.0 \text{ nm}$ can accommodate Na^+ intercalation, with $\text{Ti}_3\text{C}_2\text{T}_x$ demonstrating reversible capacity of $\sim 100 \text{ mAh g}^{-1}$ in sodium half-cells [57].

Zhang et al. prepared MXene/ SnS_2 composites via hydrothermal synthesis for sodium-ion battery anodes, with the optimized composite (MXene: $\text{SnS}_2 = 5:1$) maintaining 120 mAh g^{-1} after 125 cycles at 0°C [53]. The MXene scaffold buffered the volume expansion of SnS_2 while maintaining structural integrity.

The development of MXene composites with expanded galleries — through intercalation of carbon nanotubes, polymers, or metal oxides — has substantially improved sodium storage performance. The hierarchical architecture of MXene/metal sulfide composites provides additional sodium storage sites through conversion reactions while the MXene matrix maintains electronic connectivity.

Zinc-Ion Hybrid Capacitors

Zinc-ion hybrid capacitors (ZHCs) combine the high capacity of Zn metal anodes with the high rate capability of capacitive cathodes, representing a promising architecture for safe, aqueous energy storage. MXene-based cathodes for ZHCs leverage the reversible Zn^{2+} intercalation and adsorption on MXene surfaces [59].

Cui et al. constructed N-doped $\text{Ti}_3\text{C}_2\text{T}_x$ wrapped with N-doped amorphous carbon through a template-guided approach. The nitrogen doping improved conductivity and electrochemical stability at anodic potentials, achieving energy density of 55 Wh kg^{-1} and power density of 3314.4 W kg^{-1} with 96.4% retention after 10,000 cycles [60]. Wang et al. developed Zn-ion capacitors using $\text{V}_3\text{CrC}_3\text{T}_x$ MXene, where Cr substitution expanded interlayer spacing and enhanced Zn^{2+} adsorption. The micro-supercapacitor on paper achieved $1680.2 \text{ mF cm}^{-2}$, energy density of 51.12 Wh cm^{-2} , and 84.5% retention after 20,000 cycles [61].

Ping et al. introduced Al^{3+} as dynamic acid-tuned pillars in $\text{Ti}_3\text{C}_2\text{T}_x$ Zn-ion capacitors, expanding interlayer spacing and enhancing pseudocapacitance. The optimized device achieved 278 F g^{-1} , energy density of 37.7 Wh kg^{-1} , and 94% retention after 10,000 cycles [62].

High-Entropy MXenes

The recent development of high-entropy MXenes — solid solutions containing multiple transition metals in the M sites — has opened new avenues for tuning electronic structure and electrochemical properties. Etman et al. synthesized $\text{Ti}_{1.1}\text{V}_{0.7}\text{Cr}_x\text{Nb}_{1.0}\text{Ta}_{0.6}\text{C}_3\text{T}_x$ high-entropy MXene, demonstrating capacity of 77 mAh g^{-1} at 0.5 A g^{-1} and 87% retention after 10,000 cycles in Zn-ion capacitors. As lithium battery anodes, the material delivered 126 mAh g^{-1} at 0.01 A g^{-1} with stability over 10,000 cycles [63].

STRUCTURAL ENGINEERING AND 3D ARCHITECTURES

Restacking Mitigation Strategies

The restacking of MXene nanosheets during electrode fabrication represents a critical challenge that reduces accessible surface area and impedes ion transport. Strategies to mitigate restacking include: (i) intercalation of spacers (CNTs, graphene, polymers); (ii) creation of 3D porous architectures via freeze-casting, template methods, and 3D printing; (iii) vertical alignment of nanosheets; and (iv) introduction of artificial defects and pores [64].

Kong et al. developed 3D porous $\text{Ti}_3\text{C}_2\text{T}_x$ films via reduced-repulsion freeze-casting, minimizing interlayer repulsion through functional group tuning and charge screening. The electrode maintained stable performance at high mass loading (16.18 mg cm^{-2}), achieving ultrahigh areal capacitance of 3731 mF cm^{-2} and energy density of $336.7 \text{ } \mu\text{Wh cm}^{-2}$ [65]. Xiao et al. constructed 3D cross-linked Zn-A-MXene films by treating MXene with Zn^{2+} and NaOH, removing -F functional groups and enabling electrostatic cross-linking. The composite achieved 465.1 F g^{-1} at 1 A g^{-1} , with all-solid-state flexible supercapacitors delivering 9.55 Wh kg^{-1} [66].

Aerogel and Foam Architectures

MXene-based aerogels combine low density with high porosity, providing extensive electrolyte-accessible surfaces and efficient ion transport channels. Shao et al. prepared MXene/rGO composite aerogels with 3D through-pores via freeze-drying, achieving mechanical strength of 16.18 MPa and capacitance of 233 F g^{-1} with 91% retention [67]. Zhang et al. fabricated $\text{Ti}_3\text{C}_2\text{T}_x/\text{rGO}/\text{Fe}_3\text{O}_4$ hybrid aerogels through one-step hydrothermal gelation, with asymmetric supercapacitors achieving 365 mF cm^{-2} and energy density of $130 \text{ } \mu\text{Wh cm}^{-2}$ with 84.5% retention after 30,000 cycles [68].

Flexible and Wearable Devices

The mechanical flexibility of MXene films, combined with their metallic conductivity, enables the fabrication of wearable energy storage devices. Ning et al. developed flexible supercapacitor electrodes comprising MXene, carbon nanocoils, and PEDOT:PSS, achieving areal capacitance of 232 mF cm^{-2} at 10 mV s^{-1} with excellent cycling stability and flexibility under various deformations [69]. Qi et al. created stretchable supercapacitors using $45 \text{ } \mu\text{m}$ MXene electrodes on pre-stretched latex substrates, achieving stretchability up to 100% over 1000 cycles through periodic wrinkle formation [70].

Figure 4 presents a comprehensive comparison of specific capacitance values for various MXene-based nanocomposites.

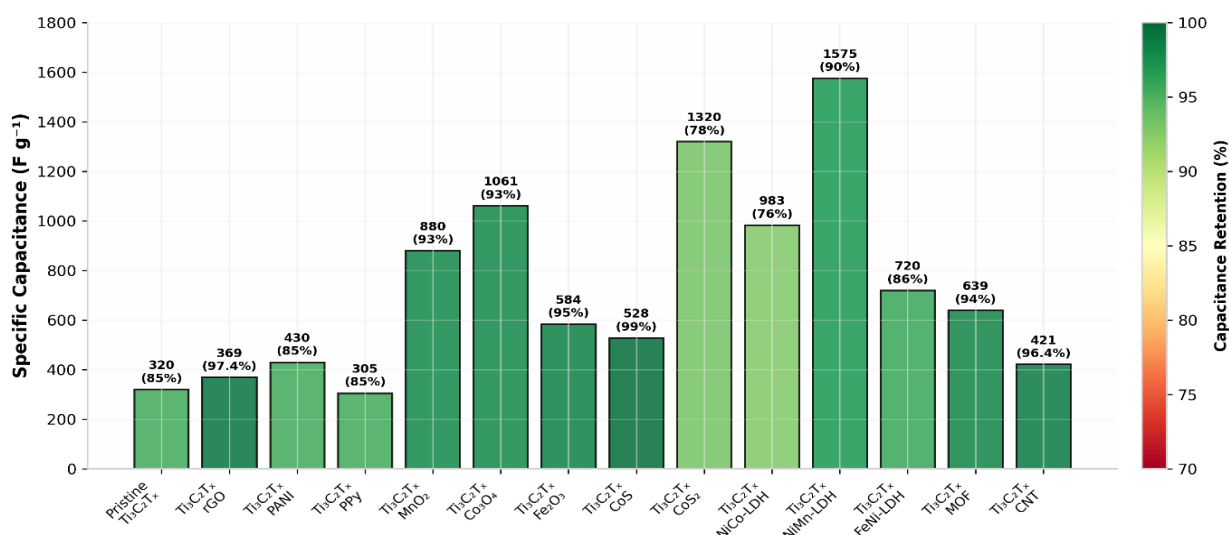


Figure 4. Specific capacitance and retention percentage of various MXene-based nanocomposites. Color intensity indicates capacitance retention after cycling. Data compiled from representative studies (2022–2025).

PERFORMANCE EVALUATION AND COMPARATIVE ANALYSIS

Electrochemical Performance Metrics

Table 1 summarizes the electrochemical performance of representative MXene-based nanocomposites across supercapacitor configurations. To ensure comparability, entries are organized by metric type, test condition, and electrode configuration.

Table 1. Electrochemical Performance of MXene-Based Supercapacitor Electrodes

Composite	Metric	Value	Unit	Test Condition	Cycle Life	Retention (%)	Ref.
Ti ₃ C ₂ T _x (pristine)	Specific capacitance	320	F g ⁻¹	2 mV s ⁻¹	5,000	85	[71]
Ti ₃ C ₂ T _x /rGO	Specific capacitance	369	F g ⁻¹	0.5 A g ⁻¹	10,000	97.4	[27]
Ti ₃ C ₂ T _x /PANI	Specific capacitance	430	F g ⁻¹	1 A g ⁻¹	10,000	85	[31]
Ti ₃ C ₂ T _x /PPy	Specific capacitance	305	F g ⁻¹	1 A g ⁻¹	10,000	85	[31]
PANI/Ti ₃ C ₂ T _x (TDP2)	Specific capacitance	452	F g ⁻¹	—	—	—	[32]
Flexible MXene electrode	Specific capacitance	532.9	F g ⁻¹	5 mV s ⁻¹	40,000	97.1	[33]
Ti ₃ C ₂ T _x /MnO ₂ /Ag	Specific capacitance	880.8	F g ⁻¹	2 A g ⁻¹	10,000	93	[35]
Co ₃ O ₄ /Nb ₂ C	Specific capacitance	1,061	F g ⁻¹	1 A g ⁻¹	1,000	93	[36]
Ti ₃ C ₂ T _x /Fe ₂ O ₃	Specific capacitance	584	F g ⁻¹	2 A g ⁻¹	10,000	95	[72]
Ti ₃ C ₂ T _x /TiO ₂ @GO	Specific capacitance	930.8	F g ⁻¹	—	50,000	98.2	[29]
CuO/βCD/MXene	Specific capacitance	1,693.43	F g ⁻¹	0.90 A g ⁻¹	10,000	86	[37]
SnO ₂ /carbon dots@MXene	Specific capacitance	1,074	F g ⁻¹	—	10,000	~100	[38]
Ti ₃ C ₂ T _x /CoS	Specific capacitance	528	F g ⁻¹	1 A g ⁻¹	20,000	99	[73]
Ti ₃ C ₂ T _x /CoS ₂	Specific capacitance	1,320	F g ⁻¹	1 A g ⁻¹	3,000	78	[74]
1T-VS ₂ /MXene	Specific capacitance	115.7	F g ⁻¹	0.8 A g ⁻¹	—	—	[40]
FeCo ₂ S ₄ /MXene	Specific capacitance	2,415.30	F g ⁻¹	—	—	90.5	[41]
Ti ₃ C ₂ T _x /NiCo-LDH	Specific capacitance	983	F g ⁻¹	2 A g ⁻¹	5,000	76	[75]
Ti ₃ C ₂ T _x /NiMn-LDH	Specific capacitance	1,575	F g ⁻¹	1 A g ⁻¹	10,000	90	[45]
Ti ₃ C ₂ T _x /FeNi-LDH	Specific capacitance	720	F g ⁻¹	1 A g ⁻¹	1,000	86	[76]
Ni MOF/Ti ₃ C ₂ T _x	Specific charge	639	C g ⁻¹	0.5 A g ⁻¹	10,000	94	[50]
MXene/rGO aerogel	Specific capacitance	233	F g ⁻¹	—	10,000	91	[28]

Table 2. MXene-Based Battery Anode Performance

Composite	Metric	Value	Unit	Current Density	Cycle Life	Retention (%)
Ti ₃ C ₂ T _x /CNT	Volumetric capacity	421	mAh cm ⁻³	20 mA g ⁻¹	10,000	96.4
Co _x Se _y /TC/rGOF	Gravimetric capacity	243.1	mAh g ⁻¹	1 A g ⁻¹	5,000	91.3
MXene/SnS ₂	Gravimetric capacity	120	mAh g ⁻¹	—	125	—
Sb/MXene	Reversible capacity	450	mAh g ⁻¹	0.1 A g ⁻¹	100	—
Ti _{1.1} V _{0.7} Cr _x Nb _{1.0} Ta _{0.6} C ₃ T _x	Capacity (ZHC)	77	mAh g ⁻¹	0.5 A g ⁻¹	10,000	87
Ti _{1.1} V _{0.7} Cr _x Nb _{1.0} Ta _{0.6} C ₃ T _x	Capacity (LIB)	126	mAh g ⁻¹	0.01 A g ⁻¹	10,000	—
Composite	Metric	Value	Unit	Current Density	Cycle Life	Retention (%)

The table 1 and 2, data reveal several important trends. First, MXene/metal sulfide and MXene/LDH composites consistently achieve the highest specific capacitances ($>1000 \text{ F g}^{-1}$) in three-electrode configurations due to the combined contributions of MXene EDL capacitance and redox-active sulfide/hydroxide pseudocapitance. Second, MXene/carbon composites exhibit superior cycling stability ($>95\%$ retention) attributable to the structural reinforcement provided by carbon scaffolds. Third, MXene/conductive polymer composites offer balanced performance with moderate capacitance and excellent rate capability.

However, it should be noted that many of these values derive from low-mass-loading three-electrode half-cells and may not translate linearly to practical full devices. The majority of cited studies employ mass loadings below 2 mg cm^{-2} , whereas commercial electrodes require $\geq 10 \text{ mg cm}^{-2}$, where ion transport and electronic resistance limitations become significant.

Energy and Power Density Analysis

The Ragone analysis (Figure 3) demonstrates that MXene-based asymmetric supercapacitors and lithium-ion capacitors occupy the critical region between conventional supercapacitors and lithium-ion batteries. NiMn-LDH/Ti₃C₂//AC lithium-ion capacitors achieve 122.7 Wh kg^{-1} , approaching the lower range of LIBs while maintaining power densities exceeding 10 kW kg^{-1} [45]. MXene-PANI asymmetric devices deliver 50.6 Wh L^{-1} with ultrahigh power density of 127 kW L^{-1} , demonstrating the potential for high-power applications [32].

It is important to distinguish between half-cell and full-device metrics. Many reported energy densities are derived from three-electrode configurations or coin-cell prototypes with minimal packaging mass. Practical packaged systems typically realize 30–50% lower energy densities due to the mass of current collectors, separators, electrolyte, and encapsulation.

Rate Capability Assessment

Rate capability — the retention of capacitance at elevated charge/discharge rates — is critical for power-intensive applications. MXene/carbon composites generally exhibit the best rate performance due to the high electrical conductivity of carbon additives. Yang et al. reported vertically aligned MXene electrodes maintaining $>200 \text{ F g}^{-1}$ at 2000 mV s^{-1} for films under $200 \text{ }\mu\text{m}$ thickness, demonstrating thickness-independent capacitance through rapid ion transport along aligned channels [77].

Nevertheless, rate capability must be evaluated at comparable mass loadings. Thin films ($<200 \text{ }\mu\text{m}$) with low active-material mass may exhibit excellent gravimetric rate performance that degrades substantially when

scaled to practical electrode thicknesses.

Figure 5 illustrates the fundamental charge storage mechanisms operating in MXene-based electrodes.

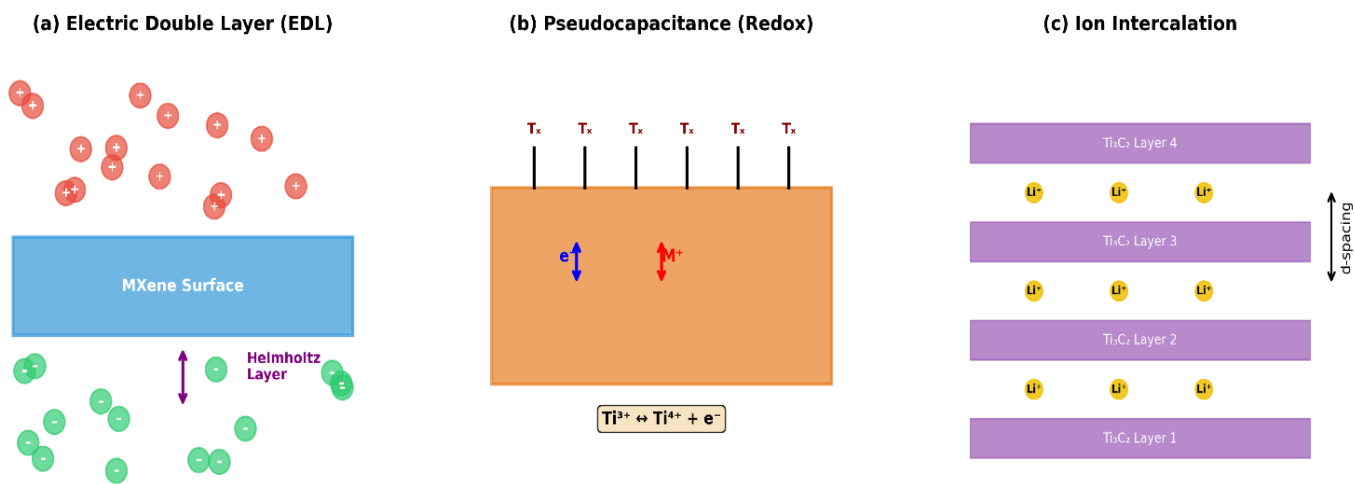


Figure 5. Schematic representation of charge storage mechanisms in MXene electrodes: (a) electric double layer formation at the electrolyte–electrode interface; (b) pseudocapacitive redox reactions involving $\text{Ti}^{3+}/\text{Ti}^{4+}$ interconversion; (c) ion intercalation between MXene layers with expanded d-spacing.

SYNTHESIS METHODOLOGY COMPARISON

Multi-Criteria Assessment

The selection of synthesis methodology profoundly impacts MXene quality, yield, safety, and scalability. Figure 6 presents a multi-criteria comparison of established synthesis routes.

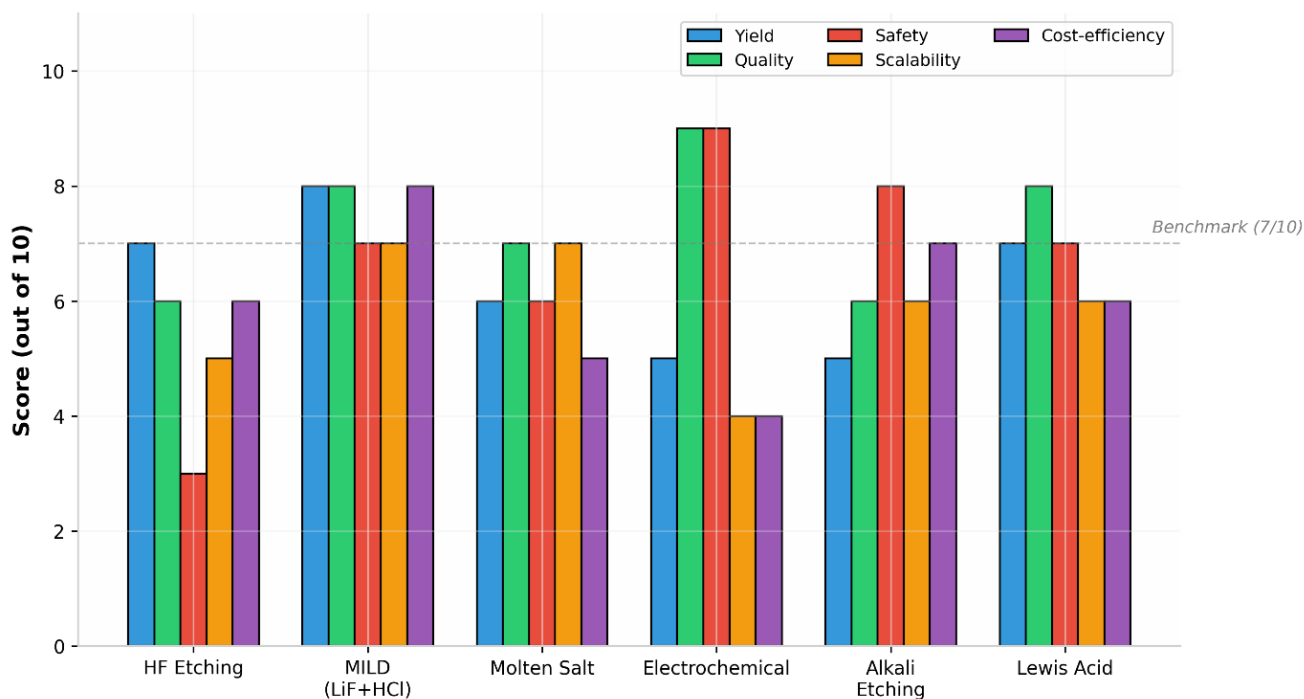


Figure 6. Comparative assessment of MXene synthesis methods across five criteria: yield, quality, safety, scalability, and cost-efficiency. Scores normalized to 10-point scale based on literature benchmarks.

The MILD method emerges as the most balanced approach, achieving high scores across yield, quality, safety,

and cost-efficiency categories. The elimination of concentrated HF significantly improves laboratory safety while the in-situ HF generation maintains etching efficacy. Electrochemical etching scores highest in quality and safety but is limited by poor scalability and high equipment costs. Molten salt methods offer unique composition control but require energy-intensive processing and present scalability challenges [78].

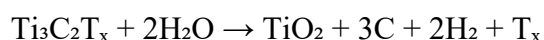
Environmental and Safety Considerations

The transition toward HF-free synthesis routes is driven by both safety imperatives and environmental regulations. Concentrated HF poses severe health hazards, with exposure limits of 0.5 ppm (8-hour TWA) established by OSHA. The MILD method reduces HF exposure risk by two orders of magnitude through dilute in-situ generation. Electrochemical and molten salt methods eliminate fluoride hazards entirely, though they introduce other considerations including electrical safety and high-temperature operations [79].

CHALLENGES AND LIMITATIONS

Oxidation Stability

MXenes, particularly $\text{Ti}_3\text{C}_2\text{T}_x$, exhibit thermodynamic instability toward oxidation in aqueous environments and ambient atmosphere. The oxidation proceeds through the reaction:



This degradation is accelerated by elevated temperatures, high pH, and dissolved oxygen. Oxidation reduces electrical conductivity, diminishes active surface area, and compromises cycling stability. Encapsulation strategies — including antioxidant coatings (L-ascorbic acid), hydrophobic surface modification, and composite formation with oxidation-resistant phases — have demonstrated partial mitigation [80].

Restacking and Aggregation

The strong van der Waals interactions between MXene nanosheets drive spontaneous restacking during drying and electrode fabrication, reducing interlayer accessibility and ion transport kinetics. While spacer incorporation and 3D architecture strategies effectively address this issue, they introduce additional processing complexity and may reduce volumetric energy density [64–66].

Scalability and Cost

The transition from laboratory-scale synthesis (gram quantities) to industrial production (kilogram/ton scales) presents formidable challenges. MAX phase precursors are commercially available but expensive (\$200–500 per kg). Etching and delamination processes require precise control over multiple parameters, and batch-to-batch variability remains a concern. Continuous flow synthesis and roll-to-roll processing are being investigated as scalable alternatives [82].

Environmental Impact

The life cycle environmental impact of MXene production encompasses mining of transition metals, energy-intensive synthesis, and disposal of etching waste streams. Life cycle assessment studies indicate that the global warming potential of MXene synthesis is dominated by precursor production and energy consumption during etching. The development of green synthesis routes using biomass-derived precursors and aqueous processing is an emerging priority [83].

Practical Mass Loading and Full-Cell Performance

A critical gap between laboratory demonstrations and commercial viability lies in mass loading. The majority of cited studies employ low mass loadings (typically $<2 \text{ mg cm}^{-2}$), which inflate gravimetric capacitance values but do not translate to thick, practical electrodes ($\geq 10 \text{ mg cm}^{-2}$) where ion transport limitations and electronic resistance become dominant. For example, Kong et al. [65] explicitly addressed this by testing 16.18

mg cm⁻² loadings, yet most entries in Table 1 lack reported mass loading, rendering direct comparison unreliable.

Furthermore, many reported energy densities are derived from three-electrode half-cells rather than full devices. Full-cell metrics must account for the mass of the counter electrode, electrolyte, and packaging; consequently, practical energy densities are typically 30–50% lower than half-cell values. Future reviews and primary studies should clearly distinguish three-electrode capacitance from two-electrode device energy and power densities.

Commercialization Barriers

Beyond materials performance, commercialization requires addressing batch-to-batch reproducibility, electrode coating uniformity, and long-term calendar life (not merely cycle life under continuous operation). The cost of MAX phase precursors (\$200–500 per kg) and energy-intensive etching/delamination steps currently positions MXenes above activated carbon and graphite in cost-per-kWh. Manufacturing routes such as continuous-flow synthesis and roll-to-roll processing remain underdeveloped [82]. Moreover, the environmental disposal of fluoride-containing etching waste from HF and MILD processes necessitates closed-loop recycling systems that are not yet industrially implemented [83].

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

a) High-Entropy and Ordered MXenes

High-entropy MXenes containing four or more transition metals in solid solution offer unprecedented opportunities for tuning electronic structure and electrochemical properties. The configurational entropy stabilizes these structures while the diverse metal centers provide multiple redox active sites. Computational screening suggests that certain high-entropy compositions may achieve capacities exceeding 500 mAh g⁻¹ for Li⁺ storage [84].

b) In-Situ Characterization and Operando Techniques

Advanced characterization methods including operando X-ray absorption spectroscopy, Raman spectroscopy, and electrochemical atomic force microscopy are elucidating the dynamic structural evolution of MXene electrodes during charge/discharge. These insights enable rational design of composites with optimized ion transport pathways and strain accommodation [85].

c) Artificial Intelligence and Machine Learning

Machine learning algorithms are accelerating MXene discovery by predicting stable compositions, optimal synthesis conditions, and electrochemical properties from computational databases. Neural network models trained on DFT calculations have identified promising MXene compositions for specific energy storage applications, reducing the experimental search space [86].

d) Integration with Emerging Technologies

The convergence of MXene energy storage with photothermal conversion, self-healing polymers, and wireless charging systems is creating multifunctional devices. Chang et al. developed photothermal supercapacitors using 3D-printed twisted Kelvin cell lattice arrays coated with graphene quantum dots and MXene nanohybrids, achieving 10.47 F cm⁻² with 3.04-fold pseudocapacitance enhancement under solar illumination [87]. Wang et al. demonstrated MXene/BOPP bilayer films combining energy storage and actuation functions with bending curvature of 1.51 cm⁻¹ under electrical stimulation [88].

CONCLUSION

This comprehensive performance evaluation of MXene-based nanocomposites for advanced energy storage reveals a field undergoing rapid maturation from fundamental discovery toward technological application.

However, the transition from laboratory record values to commercial systems requires rigorous attention to mass loading, full-device metrics, and manufacturing scalability. The key conclusions are:

- a. Synthesis optimization: The MILD method represents the current benchmark for MXene synthesis, balancing quality, yield, safety, and scalability. Emerging HF-free routes including electrochemical and molten salt etching offer promising alternatives for specific applications.
- b. Composite performance: MXene/metal sulfide and MXene/LDH composites achieve the highest specific capacitances ($>1500 \text{ F g}^{-1}$ in optimized three-electrode cells), while MXene/carbon and MXene/conductive polymer composites demonstrate superior cycling stability ($>95\%$ retention after 10,000 cycles). To be precise it should be noted that many high-capacitance values derive from low-mass-loading three-electrode configurations and may not scale linearly to practical devices.
- c. Device-level metrics: Asymmetric supercapacitors and lithium-ion capacitors based on MXene composites achieve reported energy densities of $50\text{--}123 \text{ Wh kg}^{-1}$ in laboratory devices. Practical packaged systems will realize substantially lower values.
- d. Critical challenges: Oxidation susceptibility, restacking during electrode fabrication, scalability constraints, and the absence of standardized reporting protocols (mass loading, active-material fraction, full-cell vs. half-cell) remain primary barriers to commercial deployment. Encapsulation strategies, 3D architecture engineering, and continuous flow synthesis are actively addressing these limitations.
- e. Future outlook: High-entropy MXenes, AI-guided materials discovery, and integration with multifunctional systems represent the most promising research frontiers, provided they are evaluated against rigorous, commercially relevant performance benchmarks rather than isolated laboratory metrics.

The versatility of MXenes as conductive, hydrophilic, and redox-active 2D platforms ensures their central role in next-generation energy storage. Through rational composite design and scalable manufacturing, MXene-based electrodes are poised to contribute significantly to the global transition toward sustainable energy systems.

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