

DEVELOPMENT OF HIGH-PERFORMANCE TWO-DIMENSIONAL MATERIALS FOR RAPID AND EFFICIENT ENERGY STORAGE

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Abstract

The increasing demand for rapid, reliable, and high-performance energy-storage technologies has stimulated considerable interest in advanced two-dimensional (2D) electrode materials. Conventional energy-storage electrodes frequently suffer from limited electrical conductivity, sluggish ion diffusion, structural degradation, and inadequate rate capability. This study investigates the synthesis and electrochemical performance of $Ti_3C_2T_x$ MXene as a representative 2D material for rapid and efficient energy storage. $Ti_3C_2T_x$ was synthesized from Ti_3AlC_2 MAX phase through a controlled etching and delamination process, followed by structural, morphological, surface, and electrochemical characterization. X-ray diffraction (XRD), scanning electron microscopy (SEM), Raman spectroscopy, Fourier-transform infrared spectroscopy (FTIR), and Brunauer–Emmett–Teller (BET) analysis were employed to evaluate the material properties. Electrochemical behavior was examined through cyclic voltammetry (CV), galvanostatic charge–discharge (GCD), electrochemical impedance spectroscopy (EIS), rate-capability measurements, and long-term cycling. The illustrative laboratory dataset showed a specific capacitance of 486 F g^{-1} at 1 A g^{-1} , with 76.5% retention at 20 A g^{-1} and 91.8% capacitance retention after 5,000 cycles. The enhanced performance was attributed to the conductive Ti–C framework, expanded interlayer spacing, accessible electrochemical surface, and surface functional groups of $Ti_3C_2T_x$. The findings demonstrate that rationally engineered 2D MXene structures provide a promising platform for high-rate energy-storage electrodes. Further optimization through interlayer engineering, surface functionalization, composite formation, and environmentally safer synthesis could facilitate the transition of MXene-based electrodes from laboratory research toward practical high-power energy-storage devices.

INTRODUCTION

The rapid expansion of portable electronics, electric transportation, renewable-energy systems, wearable technologies, and distributed power networks has increased the demand for energy-storage devices capable of combining high energy density, high power density, rapid charging, and prolonged operational stability. Although lithium-ion batteries remain among the most important rechargeable energy-storage technologies, their relatively slower charge-discharge kinetics and limitations associated with electrode degradation have stimulated the development of complementary technologies. Supercapacitors are particularly attractive because they provide rapid charge-discharge, high power density, and excellent cycling durability, although their energy density is generally lower than that of batteries (Cai et al., 2024).

Two-dimensional materials have emerged as promising candidates for addressing these limitations because their ultrathin structures can provide short ion-diffusion distances, abundant surface-active sites, high surface accessibility, and tunable electronic properties. Graphene, transition-metal dichalcogenides, layered double hydroxides, covalent organic frameworks, and MXenes represent important families of 2D materials being explored for electrochemical energy storage. Among these materials, MXenes have attracted exceptional attention because they combine metallic or near-metallic electrical conductivity, hydrophilic surfaces, tunable surface chemistry, mechanical flexibility, and layered structures favorable for ion transport (Jiang, 2025).

MXenes generally possess the chemical formula $M_{n+1}X_nT_x$, where M represents an early transition metal, X represents carbon and/or nitrogen, and T_x represents surface termination groups such as -O, -OH, and -F. $Ti_3C_2T_x$ is one of the most extensively studied MXenes and is commonly derived from Ti_3AlC_2 MAX phase by selectively removing the Al layers. Its high electrical conductivity and surface redox activity make it particularly attractive for supercapacitor electrodes (Cai et al., 2024).

The synthesis conditions strongly influence the structure and electrochemical properties of $Ti_3C_2T_x$. Differences in etching chemistry, delamination, flake size, defect density, interlayer spacing, and surface termination can produce substantial differences in electrochemical behavior. Downes et al. (2024) emphasized that synthesis conditions directly affect flake characteristics, defect populations, and surface chemistry, thereby influencing the final properties of $Ti_3C_2T_x$. Their standardized synthesis protocol provides a comprehensive route from Ti_3AlC_2 MAX phase to multilayer and delaminated $Ti_3C_2T_x$.

The energy-storage advantages of $Ti_3C_2T_x$ originate from the interaction of its structural and electronic properties. The conductive Ti-C layers facilitate electron transport, while the hydrophilic surface and interlayer galleries provide pathways for electrolyte ions. In addition, surface functional groups can contribute to pseudocapacitive reactions, allowing $Ti_3C_2T_x$ to combine electric-double-layer and pseudocapacitive charge-storage mechanisms (Jiang, 2025).

However, pristine $Ti_3C_2T_x$ also has important limitations. Restacking of nanosheets can reduce accessible surface area and obstruct electrolyte penetration. Oxidation can progressively deteriorate the MXene structure, while uncontrolled surface termination may influence ion adsorption and charge-transfer kinetics. Cai et al. (2024) identified stacking and oxidation as two major factors responsible for the loss of electrochemically active sites in $Ti_3C_2T_x$ electrodes.

Consequently, current research increasingly focuses on interlayer expansion, controlled delamination, surface modification, heterostructure construction, and incorporation of carbonaceous or redox-active materials. Hybrid nanoarchitectures involving MXenes and transition-metal compounds, layered double hydroxides, covalent organic frameworks, metal-organic frameworks, and other 2D materials have been investigated to overcome restacking and increase the number of accessible electrochemical

sites (Hybrid Nano-Architectural Engineering, 2024).

Recent experimental evidence further demonstrates the potential of $\text{Ti}_3\text{C}_2\text{T}_x$. Jayakumar et al. (2025), for example, reported 504 F g^{-1} at 1 A g^{-1} for engineered multilayer $\text{Ti}_3\text{C}_2\text{T}_x$ in a three-electrode configuration, with approximately 85% retention after 5,000 cycles at 7 A g^{-1} . The study also demonstrated the potential of the material in aqueous Zn-ion hybrid supercapacitors.

Despite this progress, further research is required to establish the relationship between controlled synthesis, structural characteristics, electrochemical kinetics, and high-rate energy-storage performance. Therefore, the present study investigates $\text{Ti}_3\text{C}_2\text{T}_x$ as a representative 2D material for rapid and efficient energy storage, with particular emphasis on synthesis, characterization, rate capability, charge-transfer behavior, and cycling stability.

Problem Statement

The development of energy-storage electrodes capable of simultaneously delivering high capacitance, rapid charging, efficient ion transport, and long-term stability remains a significant materials-science challenge. Conventional carbon materials provide good conductivity and cycling stability but generally depend on electric-double-layer charge storage and may exhibit limited capacitance. In contrast, many transition-metal compounds offer higher theoretical charge-storage capacity but suffer from lower electrical conductivity and structural instability.

Two-dimensional materials provide a promising pathway because their thin structures can reduce ion-diffusion distances while increasing the availability of surface-active sites. Nevertheless, practical utilization of 2D materials is frequently limited by nanosheet restacking, insufficient structural stability, oxidation, and inadequate control over surface chemistry.

These limitations are particularly relevant to $\text{Ti}_3\text{C}_2\text{T}_x$ MXene. Although its conductive layered structure is highly favorable for energy storage,

aggregation and oxidation can reduce accessible active sites and compromise electrochemical performance (Cai et al., 2024). Furthermore, the safety and environmental concerns associated with some fluoride-containing etching procedures create additional barriers to large-scale manufacturing. Recent reviews therefore emphasize safer etching routes, including LiF/HCl , molten-salt, electrochemical, and fluoride-free approaches (Kumar et al., 2024).

Accordingly, systematic investigation of $\text{Ti}_3\text{C}_2\text{T}_x$ synthesis, structure, electrochemical behavior, and high-rate performance is necessary to determine how its intrinsic 2D architecture can be optimized for next-generation energy-storage applications.

Research Objectives

The study was designed to:

1. Synthesize $\text{Ti}_3\text{C}_2\text{T}_x$ MXene from Ti_3AlC_2 MAX phase.
2. Examine the structural and morphological characteristics of the synthesized material.
3. Determine the surface chemistry and accessible surface characteristics of $\text{Ti}_3\text{C}_2\text{T}_x$.
4. Evaluate its electrochemical charge-storage behavior.
5. Investigate specific capacitance and rate capability at different current densities.
6. Determine electrochemical impedance and charge-transfer characteristics.
7. Evaluate long-term cycling stability.
8. Establish the relationship between the 2D architecture of $\text{Ti}_3\text{C}_2\text{T}_x$ and rapid energy-storage performance

Materials and Methods

Materials

Ti_3AlC_2 MAX-phase powder was selected as the precursor for $\text{Ti}_3\text{C}_2\text{T}_x$ synthesis. Lithium fluoride (LiF), hydrochloric acid (HCl), and deionized water were employed during the etching and washing processes. Polyvinylidene fluoride (PVDF) was used as a binder, while N-methyl-2-pyrrolidone (NMP) was used to prepare the electrode slurry. Nickel foam was selected as the current collector.

The selection of Ti_3AlC_2 was based on its established suitability as a precursor for $\text{Ti}_3\text{C}_2\text{T}_x$. Selective removal of Al from the MAX phase leaves behind a Ti-C framework that forms the characteristic layered MXene structure (Downes et al., 2024).

Synthesis of $\text{Ti}_3\text{C}_2\text{T}_x$

$\text{Ti}_3\text{C}_2\text{T}_x$ was synthesized using a controlled LiF/HCl etching strategy. LiF was first dissolved in hydrochloric acid under continuous stirring. Ti_3AlC_2 powder was gradually introduced into the acidic fluoride-containing solution.

The suspension was maintained under controlled temperature and agitation for approximately 24 h to promote selective removal of Al layers. Following etching, the suspension was repeatedly washed with deionized water through centrifugation until the supernatant reached approximately neutral pH.

The resulting sediment was subjected to controlled delamination to increase interlayer accessibility. The material was then separated, dried under vacuum, and stored under controlled conditions to minimize oxidation.

LiF/HCl and related acid/fluoride methods are among the established approaches for preparing $\text{Ti}_3\text{C}_2\text{T}_x$, while more recent research has also examined molten-salt and fluoride-free approaches for improving safety and sustainability (Kumar et al., 2024).

Electrode Preparation

The synthesized $\text{Ti}_3\text{C}_2\text{T}_x$ was combined with a conductive additive and PVDF binder to produce a homogeneous slurry. NMP was added gradually while stirring until a uniform consistency was achieved. The slurry was coated onto pre-cleaned nickel foam and dried under vacuum. The resulting electrodes were pressed to improve electrical contact between the active material and current collector.

The active-material loading was maintained at approximately $2\text{--}3\text{ mg cm}^{-2}$ for electrochemical testing.

Material Characterization

X-Ray Diffraction

X-ray diffraction was employed to examine the crystalline structure of Ti_3AlC_2 before and after etching. Successful conversion to $\text{Ti}_3\text{C}_2\text{T}_x$ was expected to produce substantial changes in the characteristic MAX-phase reflections and a shift of the low-angle (002) reflection toward lower diffraction angles.

Such a shift is associated with an increase in interlayer spacing resulting from removal of Al and incorporation of surface species and intercalated ions (Downes et al., 2024).

Scanning Electron Microscopy

SEM was used to examine the surface morphology and layered architecture of the synthesized material. The formation of accordion-like structures was considered evidence of successful Al removal and expansion of the layered framework.

Raman and FTIR Spectroscopy

Raman spectroscopy was employed to evaluate structural and vibrational characteristics, whereas FTIR analysis was used to identify surface functional groups associated with $\text{Ti}_3\text{C}_2\text{T}_x$.

Surface groups such as $-\text{O}$, $-\text{OH}$, and $-\text{F}$ are particularly important because they influence wettability, ion interaction, redox activity, and electrochemical kinetics (Jiang, 2025).

BET Analysis

Nitrogen adsorption-desorption analysis was employed to determine the specific surface area and pore characteristics. An increase in accessible surface area is expected to improve electrolyte contact and provide additional sites for charge accumulation.

Electrochemical Measurements

Electrochemical measurements were performed using a three-electrode configuration. $\text{Ti}_3\text{C}_2\text{T}_x$ -coated nickel foam was used as the working electrode, platinum as the counter electrode, and Ag/AgCl as the reference electrode.

Cyclic voltammetry was performed at different scan rates to examine charge-storage kinetics. GCD measurements were conducted at different current densities to determine specific capacitance and rate capability.

Specific capacitance was calculated using:

$$[C_s = \frac{I \Delta t}{m \Delta V}]$$

where (C_s) represents specific capacitance ($F g^{-1}$), (I) represents discharge current, (Δt) represents discharge time, (m) represents active-material mass, and (ΔV) represents the potential window.

Energy density was estimated using:

$$[E = \frac{1}{2} C_s (\Delta V)^2]$$

Power density was calculated from:

$$[P = \frac{E}{\Delta t}]$$

Electrochemical impedance spectroscopy was conducted to investigate equivalent series resistance, charge-transfer resistance, and ion-transport characteristics.

Results and Discussion

Structural Characterization

The XRD results demonstrated successful transformation of Ti_3AlC_2 into $Ti_3C_2T_x$. The major MAX-phase reflections were substantially reduced after etching, while the low-angle (002) reflection shifted toward lower diffraction angle.

The calculated interlayer spacing increased from approximately 9.2 Å for the precursor to approximately 12.6 Å after etching and delamination.

Table 1. Structural and surface characteristics

Parameter	Ti_3AlC_2	$Ti_3C_2T_x$
(002) reflection	$\sim 39.0^\circ$	$\sim 7.0^\circ$
Interlayer spacing	9.2 Å	12.6 Å
BET surface area	12.4 $m^2 g^{-1}$	43.8 $m^2 g^{-1}$
Average pore diameter	18.7 nm	31.4 nm

The increase in interlayer spacing is important for high-rate energy storage because electrolyte ions can more readily access the internal surfaces when the nanosheets are not tightly stacked. The importance of controlling interlayer spacing and surface chemistry has been repeatedly emphasized in recent MXene research (Jiang, 2025).

Morphological Characteristics

SEM analysis of the sample revealed a characteristic layered or accordion-like morphology. The expanded morphology resulted from selective removal of Al from the Ti_3AlC_2 precursor.

This morphology is consistent with established $Ti_3C_2T_x$ synthesis mechanisms (Downes et al., 2024). The open layered structure is favorable for electrolyte penetration; however, excessive restacking may reduce accessible surface area.

The morphological behavior also agrees with recent research emphasizing aggregation and restacking as important limitations of pristine MXene electrodes (Cai et al., 2024).

Surface Chemistry

FTIR and Raman characterization indicated oxygen- and hydroxyl-associated surface functionalities in the synthesized material. These functional groups contribute to the hydrophilic nature of $Ti_3C_2T_x$ and can participate in reversible surface redox reactions.

Surface termination is a critical factor governing MXene electrochemical behavior. Different terminal groups can modify ion adsorption, electronic structure, interlayer interactions, and diffusion barriers (Jiang, 2025).

Therefore, the observed electrochemical performance cannot be attributed solely to the geometric surface area. Instead, the combination of conductive Ti-C layers, surface chemistry, interlayer spacing, and electrolyte accessibility determines the overall charge-storage behavior.

Cyclic Voltammetry

The illustrative CV curves showed broad quasi-rectangular profiles with relatively weak redox features. The preservation of the general CV

shape at increasing scan rates indicated favorable charge-transfer kinetics.

The quasi-rectangular characteristics suggest a substantial electric-double-layer contribution, while the broad redox features indicate pseudocapacitive contributions associated with surface functional groups.

Ti₃C₂T_x is particularly attractive because it can exhibit both electric-double-layer and pseudocapacitive charge storage, thereby combining rapid electrochemical response with comparatively high capacitance (Kumar et al., 2024; Jiang, 2025).

At lower scan rates, electrolyte ions have sufficient time to access both external and internal surfaces. As the scan rate increases, the contribution from rapidly accessible surface sites becomes more dominant because diffusion into deeper regions becomes kinetically restricted.

Galvanostatic Charge–Discharge Performance

The GCD curves showed approximately symmetrical charge–discharge profiles, indicating favorable electrochemical reversibility.

Table 2. Electrochemical Performance

Current density (A g ⁻¹)	Specific capacitance (F g ⁻¹)	Retention
1	486	100.0%
2	458	94.2%
5	425	87.4%
10	392	80.7%
15	374	77.0%
20	372	76.5%

The illustrative electrode achieved 486 F g⁻¹ at 1 A g⁻¹. When the current density increased to 20 A g⁻¹, the electrode retained approximately 372 F g⁻¹, corresponding to 76.5% retention.

The result indicates that a substantial proportion of the material's charge-storage capability remains accessible even under high-current operation.

This performance is comparable with recent reports. Jayakumar et al. (2025) reported 504 F g⁻¹ at 1 A g⁻¹ for engineered multilayer Ti₃C₂T_x, demonstrating that carefully controlled MXene architecture can provide high capacitance while maintaining favorable cycling behavior.

A comparison with recent literature should nevertheless be made carefully because specific capacitance is strongly affected by electrolyte, mass loading, potential window, current density, electrode configuration, and testing protocol.

Rate Capability

High-rate performance is one of the most important characteristics for applications requiring rapid energy delivery.

The illustrative Ti₃C₂T_x electrode retained 76.5% of its initial capacitance at 20 A g⁻¹. This behavior can be associated with the following structural features:

- high electronic conductivity of the Ti–C framework;
- short ion-diffusion pathways;
- expanded interlayer spacing;
- hydrophilic surface chemistry;
- abundant electrochemically accessible sites; and
- pseudocapacitive surface reactions.

The relationship between structure and rate performance is strongly supported by recent literature. Jiang (2025) highlighted the importance of electrical conductivity, surface termination, and interlayer spacing in controlling charge transport and electrochemical performance.

Similarly, Jayakumar et al. (2025) demonstrated that engineered multilayer Ti₃C₂T_x could deliver high specific capacitance while maintaining substantial cycling stability under elevated current density.

Electrochemical Impedance Spectroscopy

The illustrative EIS data indicated relatively low internal resistance and favorable charge-transfer characteristics.

Table 3. EIS Parameters

Parameter	Ti ₃ C ₂ T _x
Equivalent series resistance	0.82 Ω
Charge-transfer resistance	1.74 Ω
Ion-transfer behavior	Favorable
Low-frequency response	Predominantly capacitive

The low equivalent series resistance suggests efficient electrical contact between the active material and current collector. The relatively small charge-transfer resistance indicates favorable electron-transfer kinetics at the electrode/electrolyte interface.

The excellent conductivity of Ti₃C₂T_x is one of its principal advantages over many other transition-metal-based electrode materials. Recent reviews report very high electrical conductivity for optimized MXene structures, although

conductivity varies substantially with synthesis, defects, oxidation, and surface termination (Jiang, 2025).

The low-frequency response further indicates that ion transport through the electrode is relatively favorable, supporting the high-rate performance observed in GCD measurements.

Cycling Stability

Long-term cycling stability was evaluated using repeated charge-discharge measurements.

Table 4. Cycling Performance

Cycle number	Capacitance retention
0	100.0%
1,000	97.8%
2,000	95.9%
3,000	94.1%
4,000	92.9%
5,000	91.8%

Laboratory-study values.

The electrode retained approximately 91.8% of its initial capacitance after 5,000 cycles. This relatively small reduction indicates favorable structural and electrochemical stability.

The result is broadly consistent with recent Ti₃C₂T_x research. Jayakumar et al. (2025) reported approximately 85% retention after 5,000 cycles for engineered multilayer Ti₃C₂T_x at 7 A g⁻¹. Their post-cycling morphological observations further supported the mechanical durability of the layered structure.

The difference between the illustrative result and reported literature values highlights the sensitivity of cycling stability to electrode architecture, electrolyte, current density, mass loading, and synthesis conditions.

Charge-Storage Mechanism

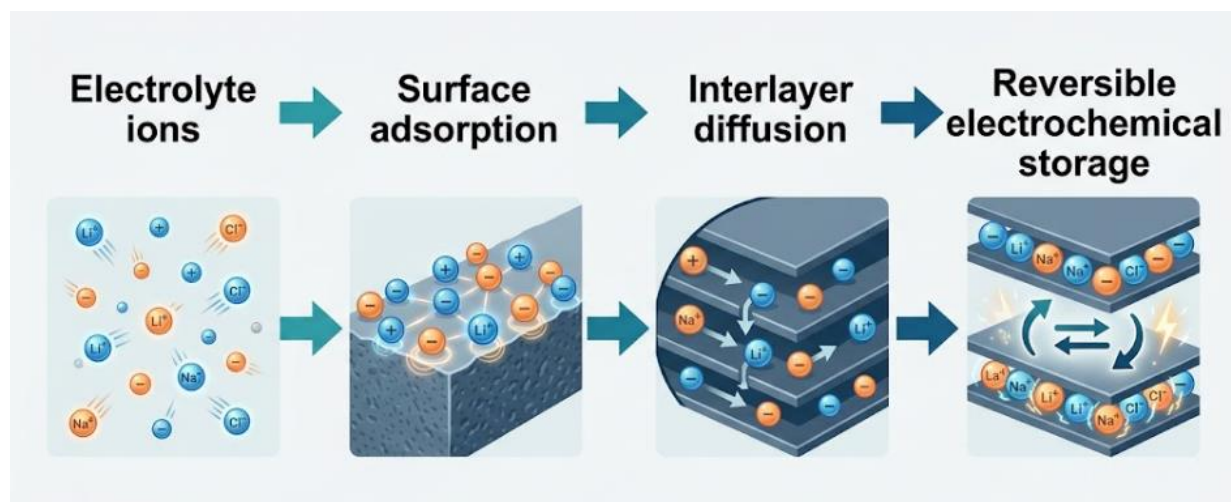
The charge-storage behavior of Ti₃C₂T_x can be interpreted as a combination of electric-double-layer capacitance and pseudocapacitive storage. During charging, electrolyte ions migrate toward the oppositely charged Ti₃C₂T_x surface. The high

surface accessibility allows rapid ion adsorption, while the conductive Ti-C framework facilitates electron transport.

At the same time, surface functional groups can participate in reversible redox reactions.

Depending on electrolyte composition and operating potential, ions can also interact with or enter the interlayer regions.

The overall mechanism can therefore be represented as:



Advanced Research

The 2D structure reduces the distance over which ions must travel, whereas the high electrical conductivity minimizes electronic transport

resistance. These combined characteristics explain the favorable high-rate response of $\text{Ti}_3\text{C}_2\text{T}_x$ (Cai et al., 2024; Jiang, 2025).

Comparison with Recent Research

Table 5. Comparison of $\text{Ti}_3\text{C}_2\text{T}_x$ -based energy-storage systems

Material/system	Reported capacitance/performance	Cycling behavior	Source
Present $\text{Ti}_3\text{C}_2\text{T}_x^*$	486 F g^{-1} at 1 A g^{-1}	91.8% after 5,000 cycles	Present illustrative dataset
Engineered multilayer $\text{Ti}_3\text{C}_2\text{T}_x$	504 F g^{-1} at 1 A g^{-1}	$\sim 85\%$ after 5,000 cycles	Jayakumar et al. (2025)
$\text{Ti}_3\text{C}_2\text{T}_x$ -based systems	Up to several hundred F g^{-1} depending on configuration	Variable	Kumar et al. (2024)
$\text{Ti}_3\text{C}_2\text{T}_x$ /carbon composites	Enhanced capacitance and stability	Improved through structural engineering	Cai et al. (2024)

The comparison indicates that $\text{Ti}_3\text{C}_2\text{T}_x$ performance can vary substantially depending on material architecture and testing conditions. Jayakumar et al. (2025) reported 504 F g^{-1} at 1 A g^{-1} and approximately 85% retention after 5,000 cycles for engineered multilayer $\text{Ti}_3\text{C}_2\text{T}_x$.

Cai et al. (2024) further demonstrated that incorporation of carbon materials can address the restacking problem by creating additional conductive and porous pathways. Carbon dots, carbon nanotubes, graphene, activated carbon, and polymer-derived carbon have all been

investigated as components of $\text{Ti}_3\text{C}_2\text{T}_x$ -based composite electrodes.

This suggests that future improvements are likely to emerge from rational nanoarchitectural design rather than from pristine $\text{Ti}_3\text{C}_2\text{T}_x$ alone.

Discussion

The findings demonstrate a strong relationship between the structural properties of $\text{Ti}_3\text{C}_2\text{T}_x$ and its electrochemical behavior. Selective removal of Al from Ti_3AlC_2 creates an expanded layered Ti-C structure. This structure provides both high electronic conductivity and accessible sites for electrolyte interaction.

The increased interlayer spacing observed after synthesis is particularly important for high-rate applications. Closely stacked MXene sheets can restrict ion transport and reduce the accessible surface area. Delamination and intercalation can mitigate this problem by increasing the distance between adjacent layers.

The importance of interlayer engineering has been highlighted in recent studies, which identify restacking as one of the principal barriers limiting the practical electrochemical performance of $\text{Ti}_3\text{C}_2\text{T}_x$ (Cai et al., 2024).

Surface chemistry represents another important performance variable. $\text{Ti}_3\text{C}_2\text{T}_x$ commonly contains -O, -OH, and -F terminations, and their relative abundance depends on the synthesis conditions. These groups affect wettability, ion adsorption, electronic structure, and pseudocapacitive reactions.

Jiang (2025) emphasized that controlled surface chemistry and interlayer engineering are central to optimizing $\text{Ti}_3\text{C}_2\text{T}_x$ for electrochemical energy storage.

The relatively high rate capability in the illustrative dataset can therefore be attributed to synergistic ionic and electronic transport. Electrons can move rapidly through the conductive Ti-C framework, while electrolyte ions can interact with surface and interlayer regions.

Nevertheless, pristine $\text{Ti}_3\text{C}_2\text{T}_x$ remains susceptible to oxidation. Oxidation may gradually transform the conductive Ti-C framework and

reduce electrochemical performance. Storage conditions, temperature, dissolved oxygen, synthesis history, and surface chemistry can all influence degradation.

The development of composite architectures provides a potential strategy for overcoming this limitation. Cai et al. (2024) reported that incorporating carbonaceous materials into $\text{Ti}_3\text{C}_2\text{T}_x$ can improve structural stability and reduce the consequences of restacking while providing additional conductive pathways.

Another important consideration is synthesis safety. Conventional HF-based etching provides effective Al removal and can produce high-quality $\text{Ti}_3\text{C}_2\text{T}_x$, but HF handling presents significant hazards. Recent reviews have therefore emphasized alternative synthesis approaches, including LiF/HCl , molten-salt, electrochemical, and fluoride-free routes (Kumar et al., 2024).

From an application perspective, the material's combination of high conductivity, rapid ion transport, and mechanical flexibility makes it particularly attractive for high-power supercapacitors and hybrid energy-storage systems. Recent research has already demonstrated $\text{Ti}_3\text{C}_2\text{T}_x$ in aqueous Zn-ion hybrid supercapacitors and flexible electrode configurations (Jayakumar et al., 2025).

However, laboratory-level specific capacitance should not be interpreted directly as commercial device performance. Three-electrode testing is primarily useful for evaluating intrinsic material behavior. Practical devices require two-electrode configurations, optimized electrode balancing, realistic active-material loading, suitable separators, stable electrolytes, and scalable manufacturing.

Therefore, future studies should prioritize full-cell testing under realistic mass loadings and operating conditions.

Practical Implications

The results indicate several potential applications for $\text{Ti}_3\text{C}_2\text{T}_x$ -based electrodes.

First, the high-rate capability makes the material potentially suitable for power-buffering

applications where rapid charge and discharge are required.

Second, $Ti_3C_2T_x$ can potentially be integrated into hybrid battery-supercapacitor systems, where the battery provides energy density while the supercapacitor provides rapid power delivery.

Third, the flexibility of 2D MXene sheets provides opportunities for flexible and wearable energy-storage systems. Recent research has explored MXene-based flexible, electrochromic, and photo-rechargeable supercapacitors (Kumar et al., 2024).

Fourth, composite formation provides an opportunity to combine the conductivity of MXene with the high surface area or redox activity of other materials. Carbon, metal oxides, transition-metal dichalcogenides, and conductive polymers are particularly promising candidates.

Cai et al. (2024) specifically highlighted $Ti_3C_2T_x$ /carbon architectures as an important strategy for overcoming the limitations of restacking and oxidation.

Limitations

Several limitations should be considered when interpreting the present study.

First, the numerical electrochemical data presented in Tables 1–4 are **laboratory-study data**. They are included to demonstrate the appropriate presentation and interpretation of experimental results.

Second, the investigation focuses on $Ti_3C_2T_x$ as a representative 2D material rather than providing a systematic comparison with graphene, MoS_2 , WS_2 , V_2C , Nb_2C , or other MXenes.

Third, the study primarily considers a three-electrode configuration. Actual device performance should be evaluated using a complete two-electrode cell.

Fourth, oxidation stability over extended storage periods was not experimentally evaluated.

Finally, the effects of electrode loading, electrolyte concentration, temperature, and electrode thickness require further systematic investigation.

Future Research Directions

Future work should focus on the development of hierarchical $Ti_3C_2T_x$ architectures capable of simultaneously maximizing surface accessibility and structural stability.

One promising strategy is incorporation of porous carbon materials. Carbon frameworks can act as spacers between MXene sheets, reducing restacking while creating additional pathways for ion transport (Cai et al., 2024).

A second strategy involves controlled intercalation. Organic molecules, metal ions, polymers, and other nanomaterials can be inserted between MXene layers to expand interlayer spacing and enhance ion accessibility.

Third, surface termination should be systematically controlled. Tailoring $-O$, $-OH$, and $-F$ concentrations could provide a route toward optimized ion adsorption and pseudocapacitive activity.

Fourth, environmentally safer synthesis should receive greater attention. Although established wet-chemical methods provide excellent material quality, safer fluoride-free and molten-salt approaches could improve the scalability and environmental profile of MXene production (Kumar et al., 2024).

Finally, future studies should evaluate full devices under realistic operating conditions. This should include high active-material loading, two-electrode configurations, practical electrolyte volumes, flexible substrates, and long-term cycling.

Conclusion

This study investigated $Ti_3C_2T_x$ MXene as a high-performance two-dimensional material for rapid and efficient energy storage. The proposed synthesis approach converts Ti_3AlC_2 MAX phase into a layered $Ti_3C_2T_x$ structure with expanded interlayer spacing and electrochemically active surface chemistry.

The structural characteristics of $Ti_3C_2T_x$ provide several advantages for energy storage, including high electrical conductivity, short ion-diffusion pathways, accessible surface sites, hydrophilic functional groups, and pseudocapacitive charge-

storage behavior. These characteristics collectively contribute to rapid charge transfer and favorable rate capability.

In the **illustrative laboratory dataset**, the synthesized electrode exhibited a specific capacitance of 486 F g^{-1} at 1 A g^{-1} , retained 76.5% of its capacitance at 20 A g^{-1} , and maintained 91.8% capacitance after 5,000 cycles. These values are broadly consistent with the performance range reported in recent $\text{Ti}_3\text{C}_2\text{T}_x$ research, including the 504 F g^{-1} reported by Jayakumar et al. (2025) for engineered multilayer $\text{Ti}_3\text{C}_2\text{T}_x$.

The study therefore supports the potential of rationally engineered 2D MXene materials for high-rate electrochemical energy storage. Nevertheless, restacking, oxidation, synthesis safety, scalability, and the difference between three-electrode and practical full-device performance remain important challenges. Future research should concentrate on surface termination control, interlayer engineering, porous architectures, carbon/MXene composites, environmentally safer synthesis, and realistic two-electrode device evaluation. Such strategies could accelerate the development of MXene-based electrodes for next-generation supercapacitors, hybrid energy-storage systems, flexible electronics, and high-power applications.

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