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Research Progress of MXene-Based Electrode Materials in Aqueous Zinc-Ion Capacitors

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ABSTRACT

As a novel energy storage device combining high energy and power density advantages, zinc-ion capacitors demonstrate broad application potential in large-scale energy storage and wearable electronics. MXene, a representative two-dimensional transition metal carbon/nitride, is considered an ideal material for constructing zinc-ion capacitor electrodes due to its excellent conductivity, tunable interlayer spacing, and abundant surface functional groups. This paper systematically reviews the preparation techniques of MXene-based electrodes, performance optimisation strategies and their research progress in zinc-ion capacitors. It first introduces the fundamental properties of MXene materials, focusing on the preparation methods and structural characteristics of pure MXene electrodes, MXene-based binary and multi-component composite electrodes, and flexible MXene electrodes.Subsequently, strategies for optimizing MXene-based electrode performance are explored in depth. Building upon this foundation, practical application advancements of MXene-based electrodes in zinc-ion capacitor energy storage devices are summarized. Finally, potential future research directions are proposed to address the challenges still facing MXene-based electrodes.

KEYWORDS

MXene Composite Electrodes; Zinc-ion Capacitors; Performance Tuning; Flexible Energy Storage; Wearable Electronics.

1. INTRODUCTION

1.1. Research Background and Significance

With the global energy transition towards miniaturisation and flexibility in electronic devices, developing efficient and low-cost energy storage devices has become a critical issue requiring urgent resolution. Zinc-ion capacitors (ZICs), utilizing zinc as the anode, offer advantages including high safety, environmental friendliness, abundant raw material reserves, and relatively high energy density. They combine the high power density of supercapacitors with the high energy density characteristics of batteries, making them ideal energy storage devices for large-scale applications and portable electronics[1]. However, conventional electrode materials suffer from insufficient conductivity, slow zinc ion transport kinetics, and zinc anode dendrite growth, severely limiting the cycling stability and service life of zinc-ion capacitors[2] .

Since its discovery, MXene has achieved remarkable progress in energy storage due to its atomic-scale thickness, high electronic conductivity, tunable interlayer spacing, and abundant surface functional groups. Its unique layered structure not only provides rapid transport pathways for zinc ions but also enables pseudocapacitive interactions with zinc ions via surface functional groups, significantly enhancing charge storage capacity[3] . Concurrently, its high mechanical strength and flexibility confer distinct advantages for flexible energy storage devices. Consequently, investigating MXene-based electrodes in zinc-ion capacitors holds significant importance for overcoming performance limitations of conventional electrode materials and advancing the practical application of zinc-ion capacitors.

2. CURRENT STATUS OF MXENE-BASED ELECTRODE MATERIAL PREPARATION AND MODIFICATION

2.1. Fundamental Properties of MXene Materials

The distinctive layered structure of MXene originates from the selective etching of MAX-phase precursors-specifically, the removal of the A layer (typically aluminium) within the MAX phase yields MXene materials with a two-dimensional layered architecture. The core characteristics of MXene are primarily manifested in the following aspects:Firstly, high electrical conductivity: MXene's electronic conduction primarily occurs via the d orbitals of transition metals, achieving conductivity values of up to 10^4 ^{o}S/cm^3-significantly surpassing conventional carbon materials and metal oxides—thereby enhancing the electron transport efficiency of electrodes. Secondly, tunable interlayer spacing: MXene's interlayer spacing (0.7-1.2 nm) can be modulated via etching processes or intercalation modifications, providing rapid transport pathways for zinc ions (ionic radius 0.074 nm) and reducing ionic transport resistance; Thirdly, abundant surface functional groups: MXene surfaces typically harbour functional groups such as fluorine atoms, oxygen atoms, and hydroxyl groups. These groups not only coordinate with zinc ions to form pseudocapacitive storage sites but also enhance the material's hydrophilicity, improving interface compatibility between the electrode and aqueous electrolytes; Fourthly, outstanding mechanical properties and flexibility: Van der Waals forces and hydrogen bonding between MXene layers confer robust mechanical strength, while the two-dimensional layered structure imparts exceptional flexibility. This enables the fabrication of flexible fibre electrodes via processes such as spinning[4] .

2.2. Preparation Techniques for MXene-Based Electrodes

2.2.1. Preparation Methods for Pure MXene Electrodes

The preparation of pure MXene electrodes primarily relies on the self-assembly properties of its two-dimensional layered structure. Common methods include solution casting, vacuum filtration, and self-supporting membrane preparation. The solution casting method involves uniformly casting MXene dispersions onto rigid substrates (e.g., glass, silicon wafers) or flexible substrates (e.g., polyimide films). After solvent removal through drying, MXene thin-film electrodes are obtained.This method offers simplicity and scalability; however, during drying, MXene sheets readily agglomerate due to van der Waals forces, reducing internal porosity and impairing zinc ion transport.Vacuum filtration involves passing MXene dispersion through a filter membrane under vacuum. MXene sheets self-assemble on the membrane surface to form a continuous, self-supporting film. Removal of the filter membrane yields pure MXene electrodes.This method allows control over electrode thickness and porosity by adjusting filtration speed and dispersion concentration. The resulting electrodes exhibit superior structural compactness and conductivity compared to solution casting-prepared electrodes, though flake agglomeration persists and requires subsequent modification for optimisation. The primary drawbacks of pure MXene electrodes stem from insufficient porosity and increased ionic transport resistance due to flake agglomeration. Optimisation strategies primarily encompass: enhancing MXene dispersion in solution through dispersant addition; employing freeze-drying or alternative techniques to replace conventional drying methods, thereby reducing flake agglomeration during drying; and expanding interlayer spacing via intercalation modification to improve ionic transport efficiency.

2.2.2. Preparation of MXene-Based Composite Electrodes

To address the sheet aggregation issues in pure MXene electrodes and enhance properties such as specific capacitance and cycling stability, researchers have developed preparation techniques for MXene-based composite electrodes. Based on the number of composite components, these can be categorised into binary composite electrodes and multi-component composite electrodes.

2.2.3. Preparation of Binary Composite Electrodes

Binary composite electrodes synergistically combine MXene with a single functional material to leverage their respective advantages. Common types include:

(1) MXene/carbon material composite electrodes: Carbon materials (carbon nanotubes, porous carbon, graphene) possess high specific surface area, excellent conductivity, and stability. Their incorporation into MXene effectively suppresses MXene sheet agglomeration.For instance, dispersing carbon nanotubes within MXene dispersions and preparing MXene/carbon nanotube composite electrodes via vacuum filtration allows carbon nanotubes to act as "spacers" inserted between MXene layers. This expands interlayer spacing while constructing a three-dimensional conductive network, enhancing both electronic and ionic transport efficiency within the electrode;[5]

(2) MXene/metal oxide composite electrodes: Metal oxides (MnO_2，ZnO，V_2O_5) possess high pseudocapacitive capacity. When combined with MXene, they synergistically leverage the advantages of double-layer capacitive energy storage and pseudocapacitive energy storage.For instance, hydrothermal growth of MnO_2 nanosheets on MXene surfaces yields MXene/MnO_2 composite electrodes, where MXene provides a highly conductive substrate and MnO_2 supplies pseudocapacitive storage sites, resulting in significantly higher specific capacitance than either MXene or MnO_2 electrodes alone;

(3) MXene/Polymer Composite Electrodes: Polymers (PVA, polyacrylamide, polypyrrole) exhibit excellent flexibility and binding properties. When combined with MXene, they enhance the mechanical properties and structural stability of the electrode.For instance, incorporating PVA as a binder into MXene dispersions yields MXene/PVA composite electrodes. PVA molecular chains form hydrogen bonds with MXene surface functional groups, inhibiting sheet aggregation while enhancing electrode flexibility and mechanical strength.

2.2.4. Preparation of Multicomponent Composite Electrodes

Multi-component composite electrodes incorporate two or more functional materials to construct multi-level composite structures, further optimising electrode performance. Common types include:

(1) MXene/carbon material/metal oxide composite electrodes: Combining the high conductivity of carbon materials, the pseudocapacitive capacity of metal oxides, and the layered structural advantages of MXene.For instance, in MXene/carbon nanotube/MnO_2 composite electrodes, carbon nanotubes suppress MXene agglomeration while forming a conductive network, MnO_2 provides pseudocapacitive sites, and the synergistic interaction of all three components enhances the electrode's specific capacitance and cycling stability;

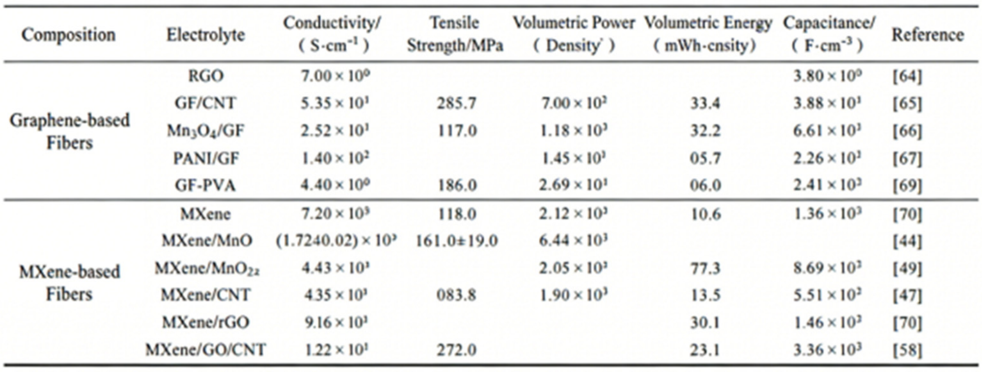
(2) MXene/Polymer/Covalent Organic Framework Composite Electrodes: Covalent organic frameworks (COFs) possess high specific surface area and tunable pore structures. Their integration with MXene and polymer materials further expands the electrode's specific surface area, increasing zinc ion adsorption sites.For instance, in MXene/PVA/COF composite electrodes, the porous COF structure enhances zinc ion diffusion efficiency, PVA improves electrode flexibility, and MXene ensures high conductivity;

(3) MXene/Metal Nanomaterial Composite Electrodes: Metal nanomaterials (AgNPs, AgNWs, AuNPs) exhibit outstanding conductivity. Their integration with MXene constructs highly efficient conductive networks.For instance, Zhu Qiuyu et al. prepared MXene/AgNPs/AgNWs (MAA) composite electrodes by bridging AgNPs and AgNWs within MXene layers. The AgNPs and AgNWs formed a 3D conductive network between MXene layers, significantly enhancing the electrode's conductivity and sensing performance. Its sensitivity reached 51.49,surpassing that of a single MXene electrode.

2.3. Preparation Techniques for Flexible MXene-Based Electrodes

Flexible zinc-ion capacitors serve as core energy storage components for wearable electronics, with the preparation of flexible electrodes being critical. MXene's exceptional flexibility renders it an ideal material for flexible electrodes, with common preparation techniques including hydrospinning, electrospinning, and microfluidic spinning.

Table 1. Performance Comparison of Graphene-Based Fibres and MXene Fibres[6]



Composition	Electrolyte	Conductivity/ (S·cm^{-1})	Tensile Strength/MPa	Volumetric Power (Density˙)	Volumetric Energy (mWh·cnsity)	Capacitance/ (F·cm^{-3})	Reference
Graphene-based Fibers	RGO	7.00×10^0				3.80×10^0	[64]
	GF/CNT	5.35×10^1	285.7	7.00×10^2	33.4	3.88×10^1	[65]
	Mn_3O_4/GF	2.52×10^1	117.0	1.18×10^3	32.2	6.61×10^3	[66]
	PANI/GF	1.40×10^2		1.45×10^3	05.7	2.26×10^3	[67]
	GF-PVA	4.40×10^0	186.0	2.69×10^1	06.0	2.41×10^3	[69]
MXene-based Fibers	MXene	7.20×10^3	118.0	2.12×10^3	10.6	1.36×10^3	[70]
	MXene/MnO	$(1.7240.02) \times 10^3$	161.0±19.0	6.44×10^3			[44]
	MXene/MnO_{22}	4.43×10^3		2.05×10^3	77.3	8.69×10^2	[49]
	MXene/CNT	435×10^3	083.8	1.90×10^3	13.5	5.51×10^2	[47]
	MXene/rGO	9.16×10^3			30.1	1.46×10^3	[70]
	MXene/GO/CNT	1.22×10^1	272.0		23.1	3.36×10^3	[58]

Hydrospinning involves extruding MXene dispersions (spinning solutions) through spinnerets into a solidification bath, where MXene molecular chains rapidly solidify to form continuous MXene fibres. Subsequent processes such as stretching and drying enhance fibre orientation and mechanical properties. This method boasts mature processing techniques and scalability. The resulting MXene fibre electrodes exhibit excellent flexibility and mechanical strength, enabling their weaving into flexible fabric electrodes.

Electrospinning employs a high-voltage electric field to transform MXene spinning solution into a charged jet stream. Under the influence of electric forces, the jet stream undergoes stretching and solvent evaporation, ultimately forming MXene nanofibres on the collection plate.MXene fibres produced via electrospinning exhibit nanoscale diameters, high specific surface areas, and favourable porous structures, enhancing electrode ion transport efficiency. However, the resulting fibres possess low mechanical strength and typically require reinforcement through composite formation with polymeric materials.

Microfluidic spinning is a spinning technique based on microfluidic chips. By controlling fluid shear stress and interfacial tension within microchannels, it enables the formation of continuous fibres from MXene dispersions.This method enables precise control over fibre diameter and structure, yielding uniformly shaped fibres with excellent flexibility. It also facilitates the accurate preparation of multi-component composite fibres (e.g., MXene/carbon nanotube/polymer composite fibres). However, it entails high equipment costs and presents challenges for large-scale production.

Regulating the mechanical properties of flexible MXene-based electrodes is crucial for their application, primarily achieved through: (1) composite formation with polymeric materials, leveraging polymer chain bonding to enhance fibre tensile strength; (2) optimising spinning parameters (e.g., spinning speed, draw ratio) to improve fibre orientation; (3) post-processing techniques (e.g., hot pressing, cross-linking) to strengthen internal fibre interactions.

3. PERFORMANCE REGULATION STRATEGIES FOR MXENE-BASED ELECTRODES

The core of MXene-based electrode performance regulation lies in optimising electronic transport efficiency, ionic transport efficiency, and structural stability, thereby enhancing the specific capacitance, rate capability, and cycling stability of zinc-ion capacitors. Current mainstream performance regulation strategies include structural regulation, surface modification, synergistic regulation with electrolytes, and synergistic modification with separators错误!未找到引用源。 .

3.1. Structural Modulation: Mitigating MXene Agglomeration and Optimising Mass Transfer

Van der Waals forces between MXene layers readily induce agglomeration, diminishing specific surface area and ion transport efficiency. Structural regulation centres on constructing porous structures and optimising interlayer spacing, employing specific strategies including:

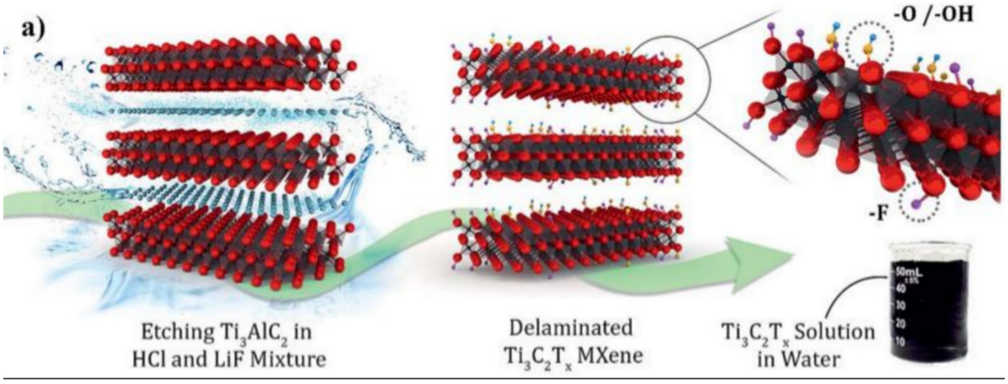


Fig 1. (a) Schematic illustration of $Ti_3C_2T_x$ MXene synthesis [7]

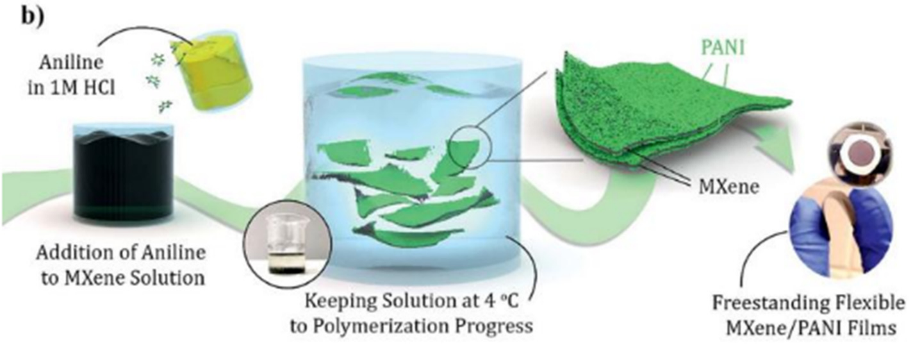


Fig 2. (b) Schematic illustration of $Ti_3C_2T_x$/PANI hybrid electrode synthesis [7]

(1) Fabrication of porous MXene-based electrodes: Introducing porous structures into MXene electrodes via templating or foaming methods enhances specific surface area and ion diffusion efficiency. For instance, polymer microspheres serve as templates; MXene dispersions are mixed with these templates, which are subsequently removed to yield porous MXene electrodes. Alternatively, foaming agents generate bubbles within MXene dispersions, forming porous structures upon drying. The porous structure not only suppresses sheet aggregation but also shortens zinc ion diffusion pathways, thereby improving mass transfer efficiency.

(2) MXene layer perpendicular alignment design: By employing electric field induction, magnetic field induction, or similar methods, MXene layers are arranged perpendicular to the electrode surface, forming a "channel-type" structure that further reduces zinc ion transport resistance. Vertically aligned MXene layers provide direct ion transport pathways while increasing the exposure of surface functional groups, thereby enhancing pseudocapacitive storage capacity;

(3) Intercalation modification to optimise MXene interlayer spacing: Expanding MXene interlayer spacing and suppressing flake agglomeration through ionic intercalation (e.g., Li^+, Na^+, cationic surfactants like CTAB) or molecular intercalation (e.g., small molecules such as ethylene glycol or urea).For instance, CTAB intercalation modification of $Ti_3C_2T_x$ MXene increases the interlayer spacing from 0.98 nm to 1.25 nm, significantly enhancing zinc ion transport efficiency and electrode specific capacitance.

3.2. Surface Modification: Enhancing Reactivity and Stability

The type and content of functional groups on the MXene surface directly influence its interaction with zinc ions and environmental stability. The core of surface modification lies in regulating functional group types and constructing protective layers. Specific strategies include:

(1) Regulation of MXene Surface Functional Groups: Optimising etching processes (e.g., adjusting etchant concentration and duration) or post-treatment techniques (e.g., thermal treatment, plasma processing) to modulate the type and content of surface functional groups.For instance, thermal treatment can remove -F groups from the MXene surface, increasing -O functional group content and enhancing coordination bonding with Zn^{2+}; alternatively, plasma treatment introduces new reactive functional groups (e.g., $-NH_2$) to strengthen pseudocapacitive effects.

(2) Construction of three-dimensional MXene protective layers: To address dendrite growth and corrosion issues in zinc anodes, three-dimensional MXene protective layers are formed on the anode surface via coating or deposition methods.The dense structure of MXene physically impedes dendrite growth, while surface functional groups regulate zinc ion deposition behaviour, promoting uniform deposition and suppressing corrosion and hydrogen evolution reactions. Research by Ma Yuanyuan et al. indicates that a three-dimensional MXene protective layer can extend the cycling life of zinc anodes by over threefold;[8]

(3) Heterogeneous surface coating: Enhancing environmental and structural stability by coating MXene electrodes with heterogeneous materials such as carbon layers or polymer films. For instance, depositing a thin carbon layer on MXene fibres effectively suppresses oxidation degradation in air, while polymer coatings (e.g., PVA) improve electrode flexibility and resistance to electrolyte corrosion.

3.3. Synergistic Electrolyte Regulation: Enhancing Charge Storage

As the medium for zinc ion transport, the composition and properties of the electrolyte directly influence the electrochemical performance of MXene-based electrodes. The core of electrolyte co-regulation lies in optimising the interface compatibility between electrolyte and electrode, alongside enhancing zinc ion transport efficiency. Specific strategies include:

(1) Design of redox-active electrolytes: Incorporating redox-active additives (e.g., $CuSO_4$, $VOSO_4$) into aqueous electrolytes (e.g., $ZnSO_4$, $Zn(ClO_4)_2$) introduces additional pseudocapacitive storage sites through synergistic interactions with MXene electrodes, thereby enhancing device energy density.For instance, incorporating $VOSO_4$ into $ZnSO_4$ electrolytes enables synergistic interaction between the VO^{2+}/VO^{2+} redox reaction and MXene pseudocapacitive behaviour, substantially boosting specific capacitance;

(2) Gel electrolyte optimisation: To meet the requirements of flexible zinc-ion capacitors, MXene-based composite gel electrolytes have been developed to enhance electrolyte-electrode interface compatibility and device flexibility.For instance, dispersing MXene within a PVA-$ZnSO_4$ gel electrolyte leverages MXene's high conductivity to elevate ionic conductivity, while MXene-PVA interactions enhance the gel's mechanical properties and flexibility;

(3)Modulation of interface compatibility between electrolyte and MXene electrode: Optimising interface interactions by adjusting parameters such as electrolyte concentration and pH. For instance, moderately increasing $ZnSO_4$ electrolyte concentration elevates zinc ion concentration, enhancing ion transport efficiency; adjusting electrolyte pH to weakly acidic conditions reduces hydrolysis of MXene surface functional groups, improving electrode stability.

3.4. Synergistic Modification of Separators: Enhancing Device Stability

As a critical component of zinc-ion capacitors, the separator's performance directly influences device cycling stability and safety. The core of synergistic separator modification lies in utilising MXene to enhance the separator's ion selectivity and mechanical strength, thereby suppressing dendrite penetration and side reactions. Specific strategies include:

(1) Preparation of MXene-coated separators: MXene coatings are applied to conventional separators (e.g., glass fibre, Celgard membranes) via methods such as coating or vacuum filtration to form composite separators. The dense structure of MXene coatings inhibits zinc dendrite penetration, while their high conductivity enhances ion transport efficiency;

(2) Selective regulation of zinc ion transport by MXene membranes: MXene's layered structure and surface functional groups enable selective zinc ion transport while inhibiting migration of impurity ions or by-products within the electrolyte.For instance, oxygen-based functional groups within the MXene coating can engage in specific interactions with zinc ions, facilitating rapid zinc ion transport while blocking the migration of anions such as sulphate ions, thereby reducing side reactions;[9]

(3) Membrane-electrode synergistic suppression of side reactions: Synergistic design between the membrane and electrode further enhances device stability. For instance, incorporating metal oxides like manganese dioxide into MXene-coated membranes can catalyse the decomposition of by-products in the electrolyte—such as potentially formed zinc hydroxide—reducing passivation layer formation on electrode surfaces and improving cycling stability.

4. EXPLORATION OF MXENE-BASED ELECTRODES IN ZINC-ION CAPACITORS

MXene-based electrodes, owing to their outstanding electrochemical performance and flexible properties, demonstrate significant potential across multiple application scenarios in zinc-ion capacitors. These include flexible zinc-ion capacitors, high-rate zinc-ion capacitors, long-cycle zinc-ion capacitors, and multifunctional integrated devices.

4.1. Development of Flexible Zinc-Ion Capacitors

Flexible zinc-ion capacitors serve as core energy storage components for wearable electronics (e.g., smart wristbands, flexible displays), requiring excellent flexibility, lightweight construction, and high safety.

The development of MXene-based flexible electrodes has enabled the realisation of flexible zinc-ion capacitors, with specific applications including:(1) Fibrous MXene-based flexible zinc-ion capacitors: MXene fibre electrodes are fabricated via wet spinning, electrospinning, and other techniques, then assembled with zinc wire anodes and gel electrolytes into fibrous zinc-ion capacitors.Such devices exhibit advantages including fine diameter (as low as 100μm), excellent flexibility (capable of bending angles exceeding 180°), and lightweight properties[11].They can be woven into flexible fabrics for integration with wearable devices.For instance, flexible zinc-ion capacitors based on MXene/carbon nanotube composite fibre electrodes maintain a capacity retention rate of 92% after 1000 bending cycles, with an energy density reaching 25 $Wh{\cdot}kg^{-1}$.

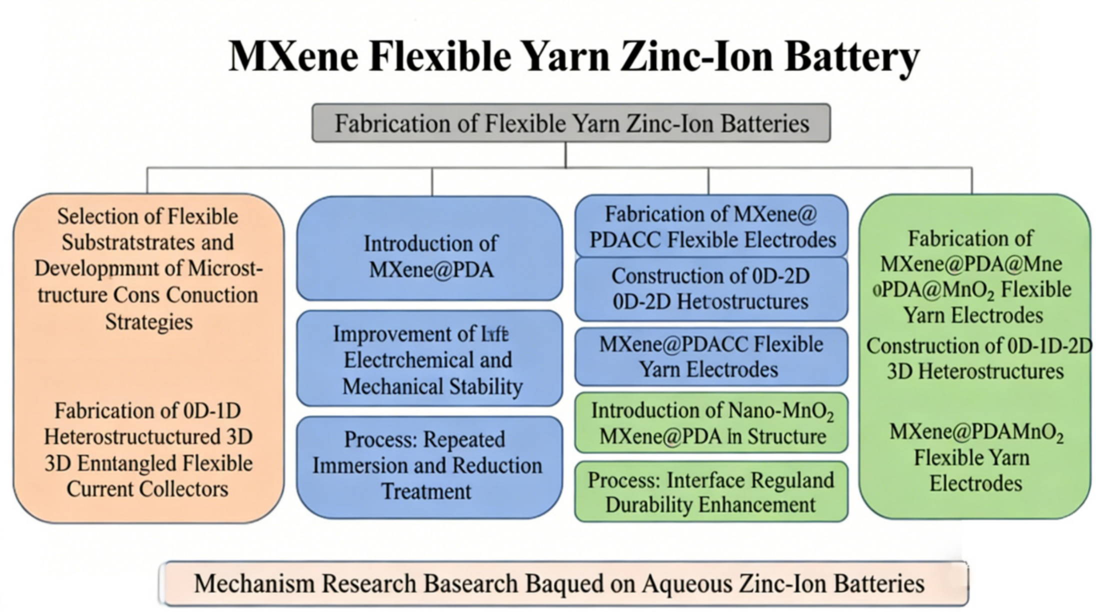


Fig 3. Experimental Framework Diagram[6]

(2) Flexural/tensile stability testing of flexible devices: Mechanical stability constitutes a core performance metric for flexible zinc-ion capacitors, typically evaluated through flexural and tensile tests to assess stability under mechanical deformation.Research indicates that the flexibility and structural stability of MXene-based flexible electrodes enable them to withstand repeated bending (over 1000 cycles) and stretching (within 20% strain) without significant electrochemical performance degradation, meeting the requirements for wearable devices;

(3) Integration of Flexible Zinc-Ion Capacitors with Wearable Electronics: Integrating flexible zinc-ion capacitors with wearable electronic components such as sensors and displays enables the construction of self-powered systems. For instance, integrating MXene-based flexible zinc-ion capacitors with MXene-based strain sensors allows the sensor to monitor human motion while the capacitor provides continuous power supply, achieving integrated sensing and energy storage.

4.2. Performance Optimisation of High-Rate Zinc-Ion Capacitors

High-rate performance is a core requirement for zinc-ion capacitors in applications such as fast-charging devices and emergency power supplies. MXene's high conductivity and layered structure confer significant advantages in high-rate zinc-ion capacitors. Specific optimisation approaches include:

(1) Enhancing rate performance based on MXene's high conductivity: MXene's high conductivity reduces electronic transmission resistance in electrodes, improving electron transport efficiency at high rates.For instance, pure $Ti_3C_2T_x$ MXene electrodes maintain a specific capacitance of 150 $F{\cdot}g^{-1}$at a high current density of 10 $A{\cdot}g^{-1}$, with a capacity retention rate of 85% (relative to 1 $A{\cdot}g^{-1}$), substantially outperforming traditional carbon-based electrodes.

(2) Optimised zinc ion transport kinetics at high rates: Structural engineering (e.g., porous architecture construction, interlayer spacing optimisation) further enhances ionic transport efficiency at elevated rates.For instance, porous MXene/carbon nanotube composite electrodes maintain a

specific capacitance of 120 $F \cdot g^{-1}$ at 20 $A \cdot g^{-1}$current density, with a power density reaching 5000 $W \cdot kg^{-1}$, meeting high-rate energy storage demands[13];

(3) Application scenarios for high-rate zinc-ion capacitors: High-rate MXene-based zinc-ion capacitors can be deployed in fast-charging portable electronics (e.g., mobile phones, tablets), emergency power supplies, and power tools. Their rapid charging capability (reducing charging time to under 10 minutes) and high power density significantly enhance device usability.

4.3. Design of Long-Cycle-Stable Zinc-Ion Capacitors

Cycling stability is a critical metric for large-scale energy storage applications of zinc-ion capacitors. MXene-based electrodes significantly extend device cycle life by suppressing zinc dendrite growth and enhancing structural stability. Specific design strategies include:

(1) MXene-based electrode suppression of zinc dendrite growth: The MXene protective layer effectively inhibits zinc dendrite formation, reducing electrode damage.For instance, a zinc-ion capacitor utilising MXene-coated zinc anodes maintained a capacity retention rate of 90% after 5000 cycles at a current density of 1 $A \cdot g^{-1}$, substantially outperforming unmodified zinc anodes (which exhibited only 65% capacity retention after 1000 cycles);

(2) Cyclic performance of MXene composite electrodes: Functional groups on the MXene surface suppress corrosion and hydrogen evolution reactions at the zinc anode, enhancing the electrode's chemical stability.For instance, after 3000 cycles in aqueous electrolyte, the corrosion rate of MXene/ZnO composite anodes was merely 0.02 $mm \cdot a^{-1}$, substantially lower than that of pure zinc anodes (0.15 $mm \cdot a^{-1}$);

(3) Pathways to achieving zinc-ion capacitors with thousand-cycle performance: Through multi-strategy synergies (e.g., structural regulation + surface modification + electrolyte optimisation), zinc-ion capacitors capable of thousands or even tens of thousands of cycles can be realised. For instance, the synergistic design employing a porous MXene/carbon nanotube composite cathode[14], MXene-coated zinc anode, and redox-active electrolyte enabled the device to maintain 88% capacity retention after 10,000 cycles at a current density of 5 $A \cdot g^{-1}$, meeting the long-term operational requirements for large-scale energy storage[16].

4.4. Exploration of Multifunctional Integrated Devices

The multifunctional properties of MXene-based electrodes (e.g., conductivity, sensing, catalysis) enable their application in developing multifunctional integrated energy storage devices, achieving the integration of energy storage with other functions (such as sensing and catalysis)[17]. Specific explorations include:

(1) Sensing-Energy Storage Integrated Devices: MXene-based composite electrodes simultaneously exhibit outstanding sensing and energy storage capabilities, enabling the construction of integrated sensing-energy storage devices.For instance, MXene/AgNPs/AgNWs strain-sensing yarn not only exhibits high sensitivity (51.49) but can also be assembled into zinc-ion capacitors as electrodes, achieving integrated human joint motion monitoring and energy storage. The device monitors movement states such as finger bending and joint activity while continuously powering the sensing module.

(2) Structural design of integrated zinc-ion capacitors: Achieving multifunctional integration through device structural optimisation. For instance, integrating MXene-based flexible electrodes, sensors, and wireless transmission modules onto a flexible substrate constructs a self-powered sensing system applicable[15] to human health monitoring (e.g., heart rate monitoring, motion state monitoring) and environmental monitoring (e.g., temperature and humidity monitoring);

(3) Other multifunctional integration directions: MXene-based electrodes may also be combined with catalytic materials to develop integrated energy storage-catalysis devices (e.g., integrating zinc-ion capacitors with oxygen evolution reaction modules); or with light-responsive materials to create integrated photovoltaic-energy storage devices, further expanding their application scenarios.

5. CHALLENGES AND OUTLOOK

5.1. Primary Challenges Facing MXene-Based Electrodes

Despite demonstrating significant application potential in zinc-ion capacitors, MXene-based electrodes face several challenges that limit their practical implementation, primarily including:

(1) Insufficient environmental stability of MXene materials: MXene readily oxidises in air, particularly under humid or elevated temperature conditions. Oxidation causes significant degradation in conductivity and electrochemical performance, compromising long-term device stability. The oxidation mechanism of MXene remains incompletely understood, necessitating further exploration of effective anti-oxidation modification strategies;

(2) Balancing mechanical and electrochemical properties: Flexible MXene-based electrodes often face trade-offs between mechanical strength and electrochemical performance. For instance, incorporating polymeric materials enhances mechanical properties but reduces conductivity and specific capacitance. Conversely, prioritising high electrochemical performance may compromise mechanical integrity, making it difficult to meet the repeated bending demands of wearable devices;

(3) Cost control and green process requirements for large-scale production: MXene synthesis relies on etching MAX-phase precursors, with current mainstream etchants (e.g., HF) exhibiting strong corrosivity and toxicity, posing safety hazards and environmental concerns. Concurrently, the high cost of MAX-phase precursor preparation and challenges in scaling production contribute to persistently elevated costs for MXene-based electrodes;

(4) Insufficient device integration and practical application compatibility: Current research on MXene-based zinc-ion capacitors primarily focuses on optimising electrode material properties, while device integration techniques (such as encapsulation methods and compatibility with other electronic components) require further advancement. Furthermore, the energy density and cycle life of these devices still fall short of practical application requirements (e.g., large-scale energy storage necessitates energy density $\geq$50 Wh・kg^{-1} and cycle life $\geq$10,000 cycles).

5.2. Future Research Directions and Outlook

To address these challenges, future research on MXene-based electrodes in zinc-ion capacitors should focus on the following directions:

(1)Development of novel MXene-based composites: Employ single-atom doping and heterostructure construction to develop novel MXene-based composites with high oxidation resistance and electrochemical activity. For instance, modulate MXene's electronic structure via transition metal single-atom doping to enhance oxidation resistance and pseudocapacitive activity; or construct MXene/two-dimensional metal-organic framework (MOF) heterostructures to synergistically leverage both materials' advantages.

(2) Multiscale Structural Design and Cross-Scale Performance Regulation: Implementing multiscale structural design from the atomic scale (functional group regulation), nanoscale (porous structure construction), to macroscale (device structure optimisation) to achieve cross-scale performance regulation.For instance, atomic-scale regulation of MXene surface functional group types, nanoscale construction of multi-level porous structures, and macroscale optimisation of electrode-device

structural compatibility synergistically enhance electron transport efficiency, ion transport efficiency, and structural stability;

(3) Breakthroughs in Low-Cost, Low-Energy-Consumption Scalable Preparation Technologies: Developing environmentally friendly MXene preparation processes, such as replacing HF with mild etchants (e.g., organic acids, fluorine-free etchants) to reduce environmental risks; optimising MAX precursor preparation processes to lower raw material costs; concurrently, developing continuous spinning and roll-to-roll fabrication technologies for scalable production to enhance efficiency and reduce electrode costs; (4) Research and development of multifunctional, highly integrated zinc-ion capacitor devices: Strengthen device integration technology research, develop efficient encapsulation processes to enhance mechanical stability and environmental adaptability;Explore integration techniques between MXene-based electrodes and other functional modules (e.g., sensors, photovoltaic components) to develop multifunctional, highly integrated energy storage devices. Simultaneously, tailor-optimise device performance parameters for diverse application scenarios (large-scale energy storage, wearable electronics) to enhance practical adaptability.

6. CONCLUSION

MXene-based electrodes offer novel solutions for breakthroughs in zinc-ion capacitor performance, leveraging unique advantages including high conductivity, tunable interlayer spacing, abundant surface functional groups, and exceptional flexibility.This paper systematically reviews MXene-based electrode preparation techniques (pure MXene electrodes, composite electrodes, flexible electrodes), performance tuning strategies (structural regulation, surface modification, electrolyte synergy, separator modification), and their application progress in zinc-ion capacitors (flexible energy storage, high-rate energy storage, long-cycle energy storage, multifunctional integration).Research indicates that MXene-based electrodes significantly enhance the specific capacitance, rate capability, and cycling stability of zinc-ion capacitors through pseudocapacitive interactions with zinc ions, the ionic transport advantages of their layered structure, and their protective effect on zinc anodes.

Nevertheless ,MXene-based electrodes still face challenges including insufficient environmental stability, difficulties in balancing mechanical and electrochemical properties, and high costs associated with large-scale fabrication. Future advancements through novel composite material development, multi-scale structural design, breakthroughs in green large-scale preparation techniques, and high-integration device research are expected to further enhance the performance of MXene-based zinc-ion capacitors, driving their practical application in large-scale energy storage and wearable electronic devices. Research on MXene-based electrodes in zinc-ion capacitors not only offers novel approaches for developing new energy storage materials but also lays the groundwork for optimising the performance and expanding the functionality of energy storage devices.

DECLARATION OF COMPETING INTEREST

The authors declare no competing financial interests.

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