

Review

Recent Advances in Tantalum Carbide MXenes: Synthesis, Structure, Properties, and Novel Applications

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Abstract: Tantalum carbide MXenes, notably $Ta_4C_3T_x$ and Ta_2CT_x , exhibit distinctive physicochemical properties that distinguish them from the well-studied $Ti_3C_2T_x$ MXene. The combination of exceptional electrochemical properties, efficient photothermal conversion, and tunable surface terminations highlights the versatility of Ta-MXenes. These characteristics render them highly valuable for versatile applications. This minireview summarizes recent progress in tantalum carbide MXenes and their composites, focusing on applications in energy storage, conversion, sensing, and biomedicine. First, synthesis methods for tantalum carbide MXenes are summarized. Subsequently, their key properties are discussed, followed by a systematic review of diverse applications. Finally, this review offers a summary and outlook on the challenges and opportunities in the field of tantalum carbide MXenes research.

Keywords: MXene; $Ta_4C_3T_x$; Ta_2CT_x ; synthesis; energy storage; energy conversion; sensor



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1. Introduction

MXenes, first discovered in 2011 [1], are a group of 2D transition metal carbides, nitrides, and carbonitrides exhibiting excellent electrical conductivity, remarkable mechanical strength, tunable hydrophilic/hydrophobic properties, and unique optical, electrical, and electromechanical characteristics, rendering them promising for a wide range of applications [2–6]. The general formula for MXene is $M_{n+1}X_n$ or $M_{n+1}X_nT_x$ (M stands for transition metals, X is C and/or N, $n = 1–3$, and T_x represents surface terminations [-OH, -F, -O, -Cl, etc.]) [7]. These terminations facilitate further surface modifications, enhancing the material's versatility. Since their discovery, MXenes have garnered significant attention for their adjustable composition and layered structure, enabling property customization and broad application potential.

So far, most studies in the MXene field have focused on $Ti_3C_2T_x$ due to its relative ease of synthesis and well-documented properties. Recently, tantalum-based MXenes have garnered significant attention due to their notable attributes compared to $Ti_3C_2T_x$. Tantalum-based MXenes follow the general formula $Ta_{n+1}C_nT_x$, where n represents the number of carbon layers. To date, two representative compositions, $Ta_4C_3T_x$ and Ta_2CT_x , have been successfully synthesized. These materials exhibit distinctive physicochemical properties. For example, $Ta_4C_3T_x$ MXene features a significantly larger interlayer distance than $Ti_3C_2T_x$ [8], which facilitates enhanced ion intercalation and diffusion processes, crucial for the performance of energy storage devices. The biocompatibility of elemental tantalum, which has driven its extensive use in clinical applications, also extends to its

MXene derivatives, enabling their application in biological systems with minimal cytotoxicity concerns. Due to its high atomic number ($Z = 73$), tantalum provides superior CT imaging effects compared to iodine-based contrast agents, enhancing its utility in diagnostic imaging. In contrast to the extensively researched $\text{Ti}_3\text{C}_2\text{T}_x$ MXene, $\text{Ta}_4\text{C}_3\text{T}_x$ exhibits distinct advantages, including an electrical conductivity six times higher than that of other MXene types [9]. These superior properties render it particularly suitable for applications in electrocatalysis, photocatalysis, and other energy conversion processes [10]. Moreover, the remarkable attributes of tantalum carbide MXenes have ensured their applicability across a range of areas, including energy storage devices [9,11], sensors [12,13], surface-enhanced Raman spectroscopy (SERS) [14,15], biomedicine [16,17], photonics and optoelectronics [18,19], and so on (Figure 1). This paper provides an overview of the advancements in tantalum carbide MXene preparation, properties, and applications. Significant attention is devoted to the innovative synthesis techniques, their wide-ranging applications, and novel strategies spanning various fields.

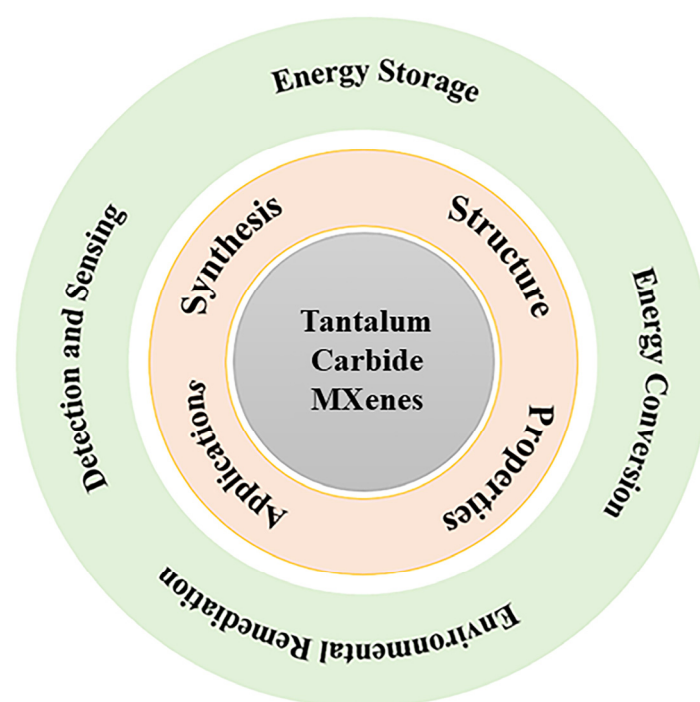


Figure 1. Brief description of tantalum carbide MXenes in various applications (pink area: the content of this review, green area: the application domain of tantalum carbide MXenes).

2. Synthesis Procedures

2.1. Synthesis of Tantalum Aluminum Carbide MAX Phase

Tantalum carbide MXenes are typically synthesized by selectively etching aluminum (Al) from their tantalum aluminum carbide MAX phase precursors. Specifically, Ta_4AlC_3 and Ta_2AlC serve as the precursors for the synthesis of $\text{Ta}_4\text{C}_3\text{T}_x$ and Ta_2CT_x MXenes, respectively. A variety of approaches have been adopted for the synthesis of Ta_4AlC_3 and Ta_2AlC MAX phases so far, most involving high-temperature sintering treatment of tantalum (Ta), aluminum (Al), and carbon (C) powders, and other materials. For example, Dai et al. employed a ball-milling technique to mix Ta, Al, and C powders in a 4:1.75:3 molar ratio at a speed of 800 rpm for 12 h. Following this, the mixed powders were pressed into a disc shape and then heated to 1500 °C in an argon-filled tube furnace at a rate of 10 °C/min for 2 h, resulting in the formation of Ta_4AlC_3 MAX phase ceramics [20]. Beyond traditional sintering approaches, hot-press sintering represents another frequently utilized technique in

the fabrication of the tantalum aluminum carbide MAX phase. Lin et al. prepared Ta_4AlC_3 ceramic through a hot-pressing method, where elemental Ta, Al, and C powders were first homogenized via ball milling for 10 h, followed by heating to 1500 °C at 15 °C/min in a flowing argon atmosphere and applying 30 MPa pressure for 1 h [21]. Syamsai et al. synthesized a Ta_4AlC_3 MAX phase through a solid-state technique, initially involving ball milling of Ta, Al, and C powders at 800 rpm, followed by hot pressing the resultant powder at 900 °C under 0.5 ton and 10^{-3} base vacuum [22]. Despite the effectiveness of hot-pressing sintering techniques in the synthesis of tantalum aluminum carbide MAX, their high costs and requirement for specialized equipment have led researchers to explore more cost-effective alternatives. Yeh et al. present a novel approach for synthesizing Ta_2AlC MAX through self-propagating high-temperature synthesis [23]. It shows that the ideal Al content (Ta:Al:C = 2:1.6:1) promotes single-phase Ta_2AlC MAX formation through exothermic combustion reactions that take place at temperatures between 1050 and 1250 °C.

2.2. Synthesis of Tantalum Carbide MXene

After the successful preparation of tantalum aluminum carbide MAX phase precursors, a widely adopted technique for producing tantalum carbide MXenes is the targeted etching of the Al components in their MAX phase. Various etching methods have been developed for tantalum carbide MXenes, with different etchants significantly influencing their morphological structures. HF etching is one of the primary methods for etching tantalum carbide MXenes, utilizing concentrated hydrofluoric acid directly. Another approach is in situ HF etching, which employs a combination of acid and fluorine-containing salts. Additionally, alkali etching and the acid-base treatment method without fluorine have been explored as viable alternatives. These approaches to synthesizing tantalum carbide MXenes from the etching of tantalum aluminum carbide MAX are depicted in Table 1.

2.2.1. Direct Hydrofluoric Acid (HF) Etching

HF is employed as a most common selective etchant to facilitate the conversion of Ta_4AlC_3 and Ta_2AlC MAX phases into $\text{Ta}_4\text{C}_3\text{T}_x$ and Ta_2CT_x MXene. The selective etching is driven by the preferential removal of Al layers, which is attributed to the comparatively lower bond energy of Al-Ta or Al-C bonds relative to the robust Ta-C bonds. This selective etching process facilitates the transformation of layered MAX phases into 2D MXene materials, ensuring the structural integrity of the transition metal carbide layers. In most cases, the etching process after HF treatment leads to the formation of a distinctive accordion-like morphology tantalum carbide MXene, which significantly enhances its surface area and expands the interlayer spacing, thereby improving its functional properties [16,24,25]. Moreover, the direct HF etching process influences the surface chemistry of tantalum carbide MXene by introducing a variety of terminal functional groups, primarily -OH, -O, and -F, which significantly influence the MXene's physicochemical properties [9,24]. This direct HF etching process consists of simple yet effective steps, including HF treatment and subsequent washing, making it accessible. However, the permeability and high toxicity of HF require that strict safety measures must be followed during use and handling.

2.2.2. In Situ HF Etching (Fluoride Salt)

Liu et al. developed a method to synthesize $\text{Ta}_4\text{C}_3\text{T}_x$ MXene etching Al from the Ta_4AlC_3 MAX phase using in situ HF generated from LiF and HCl [26]. This approach replaces the use of highly toxic HF with milder HCl for the synthesis of $\text{Ta}_4\text{C}_3\text{T}_x$ MXene. Considering the higher exfoliation energy of Ta_4AlC_3 relative to conventional MAXs (such as Ti_3AlC_2 , Zr_3AlC_2 , Ti_2AlN and Ti_2AlC_2) [27], the milder HCl/LiF etching process was usually conducted under high temperature and pressure. Specifically, a hydrothermal treatment at 180 °C for 20 h was implemented to achieve the effective etching [13,26].

Rafieerad et al. developed a method to etching Ta_4AlC_3 using 12 M HCl and 4 M NaF as etchants at 60 °C for 48 h [28]. The resultant MXene nanosheets were further treated by hydrothermal process to obtain $Ta_4C_3T_x$ MXene quantum dots.

2.2.3. Fluorine-Free Etching

For safer and more practical applications, fluorine-free etching synthesis has utilized alkali species to extract Al from tantalum aluminum carbide and synthesize tantalum carbide MXene. Vijayaprabakaran et al. developed a straightforward alkali-assisted hydrothermal method for synthesizing Ta_2C MXene [10]. Ta_2AlC MAX phase powder was uniformly dispersed in a concentrated KOH solution, subjected to hydrothermal treatment at 150 °C for 24 h in an autoclave, centrifuged, and thoroughly washed with deionized water to achieve a neutral pH, ensuring complete removal of residual alkaline components, ultimately yielding etched Ta_2C MXene. Rafieerad et al. employed a modified alkaline-based etching method to synthesized $Ta_4C_3T_x$ MXene through a two-step acidic/alkaline (HCl/KOH) etching [11]. The Ta_4AlC_3 MAX phase powder underwent a sequential chemical treatment involving 6 M HCl followed by 6 M KOH to produce an exfoliated nanocomposite material. These fluorine-free etching methods provide environmentally friendly alternatives for the synthesis of tantalum carbide MXene.

Table 1. The different preparation approaches for synthesizing tantalum carbide MXene.

Precursor	Etchant	Reaction Condition	Ref.
10 g Ta_4AlC_3 power	40% HF	Stirred for 72 h at room temperature (RT)	[8]
1 g Ta_4AlC_3 powder	20 mL 20% HF	Stirred for 4 h	[29]
2 g Ta_4AlC_3 powder	50 mL HF	Stirred at 45 °C for 96 h	[9]
1 g of Ta_4AlC_3 precursor	20 mL 45% HF	Stirred for 120 h at 50 °C	[30]
2 g of Ta_4AlC_3	50 mL 45% HF	Stirred at 45 °C for 120 h	[12]
2 g Ta_4AlC_3	20 mL 9 M HCl + 2 g LiF	Stirred at 35 °C for 72 h	[31]
1 g Ta_4AlC_3	50 wt% HF	Stirred at 40 °C for 96 h	[24]
0.5 g Ta_4AlC_3	20 mL of 40% HF	Stirred for 96 h at RT	[22]
1 g Ta_4AlC_3 powder	40 mL 49 wt% HF	Stirred for 72 h at RT	[32]
Ta_4AlC_3	40% HF	Stirred for 96 h at RT	[20]
Ta_4AlC_3	HF	Etched for 4 days at RT	[33]
2 g Ta_4AlC_3	40 mL 40 v/v% HF	Stirred for 4 days	[34]
1 g Ta_4AlC_3	12 mL 40 wt% HF	Stirred for 4 days	[14]
Ta_4AlC_3	40% HF	Etched for 4 days	[18]
1 g Ta_2AlC	5 mL 49 wt% HF	Stirred for 1 day at RT	[16]
Ta_2AlC	HF	Etching	[35]
1 g Ta_4AlC_3	30 mL 40% HF	Stirred for 72 h at RT	[17]
1 g Ta_4AlC_3	20 mL 50 wt% HF	Stirred at 40 °C for 96 h	[36]
0.5 g Ta_4AlC_3	15 mL (36–38 wt%) + 0.6 g LiF	Hydrothermal reacted at 180 °C for 20 h	[13]
0.5 g Ta_4AlC_3	15 mL~38 wt% HCl + 0.6 g LiF	Hydrothermal reacted at 180 °C for 20 h	[26]
2 g Ta_4AlC_3	40 HCl + mL 3.2 g LiF	Reacted for 48 h	[37]
Ta_4AlC_3	12 M HCl and 4 M NaF	Reacted at 60 °C for 48 h	[28]
Ta_4AlC_3	6 M HCl, 6 M KOH	Shaking in HCl at 37 °C for 72 h, Freeze dried, treating in KOH at RT for 90 h	[11]
1.5 g Ta_2AlC	KOH	Hydrothermal reacted at 150 °C for 24 h	[10]

2.3. Delamination of Tantalum Carbide MXene

Following the etching process, tantalum carbide MXene commonly presents an accordion-like morphology. The accordion-like multilayered MXene requires delamination for effective exploration of its properties. For multilayer MXene, increasing the interlayer spacing weakens van der Waals forces, enabling easy separation into single or few-layered flakes through simple methods like shaking or ultrasonication. Delamination of multiple layers further requires intercalating agents to expand the interlayer spacing (Figure 2). The most commonly used intercalating agents are tetramethylammonium hydroxide (TMAOH), tetrapropylammonium hydroxide (TPAOH), and tetrabutylammonium hydroxide (TBAOH). These intercalating agents can further increase the interlayer distance of MXene, promoting the exfoliation of MXene nanosheets, thereby obtaining thinner MXene nanosheets. The enlarged interlayer can be identified by XRD. For example, in Liu's report, the diffraction peak of the tantalum carbide (002) crystal plane exhibited a shift of 2° toward the lower-angle region after etching and intercalation, indicating an expansion in the interlayer spacing [26]. The multiple preparation techniques for delamination of tantalum carbide MXene are depicted in Table 2.

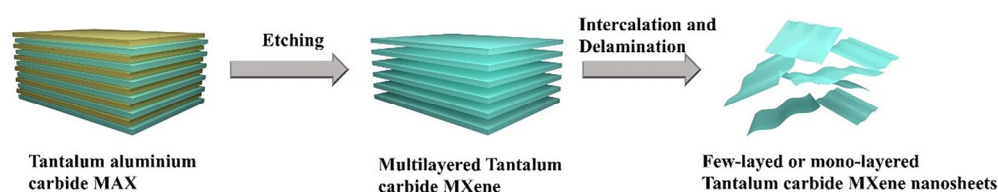


Figure 2. Schematic illustration of the synthesis of tantalum carbide MXene. (brown: the Al layer, blue: the tantalum carbide MXene).

Table 2. Multiple preparation techniques for delamination of tantalum carbide MXene.

Precursor	Intercalating Agents	Intercalation and Delamination Method	Product	Ref.
$Ta_4C_3T_x$	TMAOH	Stirred for 24 h	2D $Ta_4C_3T_x$	[12]
$Ta_4C_3T_x$	TPAOH	Stirring overnight	$Ta_4C_3T_x$ nanosheet	[29]
$Ta_4C_3T_x$	TPAOH	Stirred for 2 days	2D $Ta_4C_3T_x$	[14]
$Ta_4C_3T_x$	TBAOH	Sonicating	few-layered or mono-layered $Ta_4C_3T_x$	[32]
$Ta_4C_3T_x$	TBAOH	Stirred for 4 h	2D $Ta_4C_3T_x$	[26]

3. Structure of Tantalum Carbide MXene

$Ta_4C_3T_x$ MXene is generally prepared by selectively etching the Al layer in its MAX phase using HF [38]. Figure 3a,b show SEM images of the microstructure of a multilayer of $Ta_4C_3T_x$ after HF etching, illustrating the successful realization of decrustation for individual grain. The HRTEM image clearly demonstrates that the crystal lattice of multilayered nanosheet with hexagonal structure and the basal plane hexagonal symmetry of the MAX phase is preserved during HF treatment (Figure 3c and inset). TEM images reveal that thin electron-transparent sheets of the delaminated $Ta_4C_3T_x$ nanosheets (Figure 3d,e) inform a typical sheet-like morphology with an average size of approximately 100 nm. Viewing the basal planes in the cross section of the TEM image (Figure 3f), the single-layered $Ta_4C_3T_x$ nanosheet is ~ 1 nm thick. The XRD pattern shows the comparison of the Ta_4AlC_3 MAX phase with $Ta_4C_3T_x$ (Figure 3g). The peak intensity of Ta_4AlC_3 was greatly reduced after HF treatment. The enlarged c lattice parameter was found to be 30.15 Å. For most of the reported HF-etched MXenes, an emerging low-angle (002) peak is observed, which implies

that the sample has been converted into MXene [25]. As illustrated in the atomic structure image, an atomic model of a free-standing Ta_4C_3 nanosheet was constructed from the Ta_4AlC_3 phase. Both top and side views of the stable atomic configuration of the 2D Ta_4C_3 nanosheet ($a = 3.13 \text{ \AA}$) are illustrated in Figure 3h and Figure 3i, respectively.

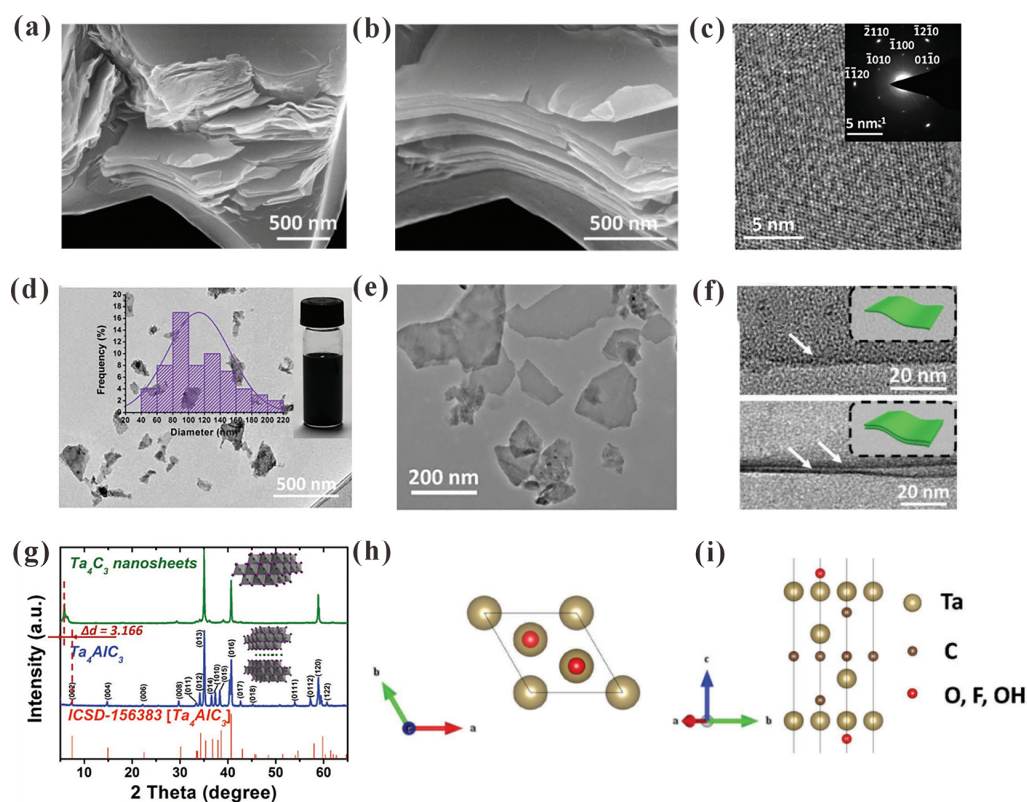


Figure 3. Structural features of $\text{Ta}_4\text{C}_3\text{T}_x$. (a,b) SEM images of layered $\text{Ta}_4\text{C}_3\text{T}_x$ after HF etching. (c) HRTEM image of multilayer $\text{Ta}_4\text{C}_3\text{T}_x$ after HF etching. Inset shows the overall SAED pattern. (d,e) TEM images of ultrathin $\text{Ta}_4\text{C}_3\text{T}_x$ nanosheets after probe sonication. Middle inset shows lateral size distribution of the $\text{Ta}_4\text{C}_3\text{T}_x$ nanosheets and right inset is a digital photo of $\text{Ta}_4\text{C}_3\text{T}_x$ nanosheets dispersed in water. (f) HRTEM images of ultrathin $\text{Ta}_4\text{C}_3\text{T}_x$ nanosheets with one layer and two layers. (g) XRD patterns of Ta_4AlC_3 phase and $\text{Ta}_4\text{C}_3\text{T}_x$ nanosheets. (h) Top and (i) side views of the surface terminated $\text{Ta}_4\text{C}_3\text{T}_x$ (T = O, F, and OH) [25]. Copyright (2017), Wiley-VCH.

4. Properties of Tantalum Carbide MXene

The crystal structures of Ta_2C and Ta_4C_3 MXene are illustrated in Figure 4. Ta_2C demonstrates the fundamental building block with a symmetric tri-layer sequence (Ta-C-Ta), featuring two Ta layers coordinating a single C interlayer. Ta_4C_3 extends this stacking principle into a seven-layer architecture with four Ta layers establishing three distinct carbon intercalation planes [39]. XRD shows that $\text{Ta}_4\text{C}_3\text{T}_x$ crystallizes in a hexagonal close-packed configuration [33]. The density functional theory calculations reveal that the total and partial density of states (DOS) of $\text{Ta}_{n+1}\text{C}_n$ MXene exhibit non-zero density of states at the Fermi level, revealing metallic conductivity characteristics. The Ta 5d orbital electrons constitute the predominant contribution to the electronic states near the Fermi level [39].

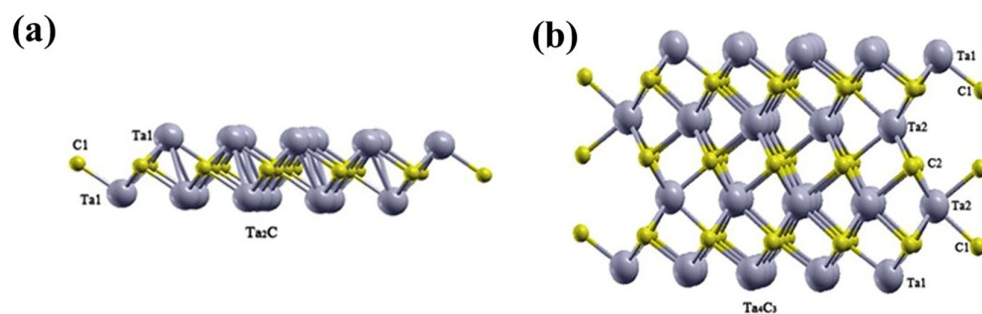


Figure 4. The atomic structure of pristine (a) Ta_2C and (b) Ta_4C_3 MXene. Permission granted for reproduction [39]. Copyright (2018), Wiley-VCH.

As for optical properties, Ta_2CT_x MXene demonstrates strong and relatively flat absorption characteristics spanning from the UV to the NIR region (400–2000 nm) [19]. Ta_4C_3 MXene displays a broad and intense optical absorption, similar to other 2D nanomaterials, including graphene and MoS_2 [25]. Moreover, Ta_2CT_x and $\text{Ta}_4\text{C}_3\text{T}_x$ MXene demonstrate outstanding nonlinear optical characteristics, highlighting their promise as photonic application materials [35,37].

Surface terminations (T_x) significantly influence the properties of tantalum carbide MXene materials. According to the research of Dong et al., the electronic properties of tantalum carbide MXenes can be modified by surface terminations [18]. As for Ta_4C_3 , upon adsorption of $-\text{O}$, the electron energy states in the upper conduction band were notably reduced, indicating a profound impact on the electronic properties. After O -termination, the overall energy bands were concentrated within the range of -8.5 eV to approximately 3 eV, with a significant downward shift in the energy level of the highest conduction band [18]. In the case of $-\text{OH}$ terminated Ta_4C_3 , a novel band δ emerged at approximately -10 eV, originating from the orbital hybridization of Ta 3d, C 2s, O 2p, and H 1s, which would endow it with broadband absorption. As for optical properties, $-\text{O}$ termination significantly enhances the absorption of Ta_4C_3 in the near-infrared region (800–1600 nm). $-\text{OH}$ termination specifically boosts absorption within the 1200–1600 nm wavelength range.

5. Multifunctional Applications of Tantalum Carbide MXene

5.1. Energy Storage

5.1.1. Lithium-Sulfur Batteries

Lithium-sulfur (Li-S) batteries are a promising next-generation energy storage technology offering ultrahigh theoretical capacity, superior energy density, and significant cost and environmental advantages over conventional lithium-ion systems. Despite their potential, Li-S batteries suffer from the polysulfide shuttle effect, slow redox kinetics, and lithium dendrite growth that raises safety risks. $\text{Ta}_4\text{C}_3\text{T}_x$ MXene has emerged as a novel Li-S battery component due to its excellent electrical conductivity and good mechanical strength. Liang et al. presents a novel bifunctional barrier design for Li-S batteries using a $\text{Ta}_4\text{C}_3\text{T}_x$ - Ta_2O_5 heterostructure [9]. The heterostructure was fabricated by H_2O_2 -mediated oxidation of $\text{Ta}_4\text{C}_3\text{T}_x$ MXene and subsequent calcination, yielding Ta_2O_5 quantum dots anchored on $\text{Ta}_4\text{C}_3\text{T}_x$. The high conductivity of $\text{Ta}_4\text{C}_3\text{T}_x$ MXene enhances Li^+ diffusion and storage. Moreover, the excellent mechanical strength suppresses Li dendrite formation, while Ta_2O_5 efficiently anchored polysulfides (Figure 5a). Owing to these merits, the $\text{Ta}_4\text{C}_3\text{T}_x$ - Ta_2O_5 @carbon polypropylene (C-PP) heterostructure exhibits remarkable electrochemical performance, with an initial capacity of $801.9 \text{ mAh}\cdot\text{g}^{-1}$ at 1 C and a remarkably low capacity degradation rate of just 0.086% across 500 cycles (Figure 5b).

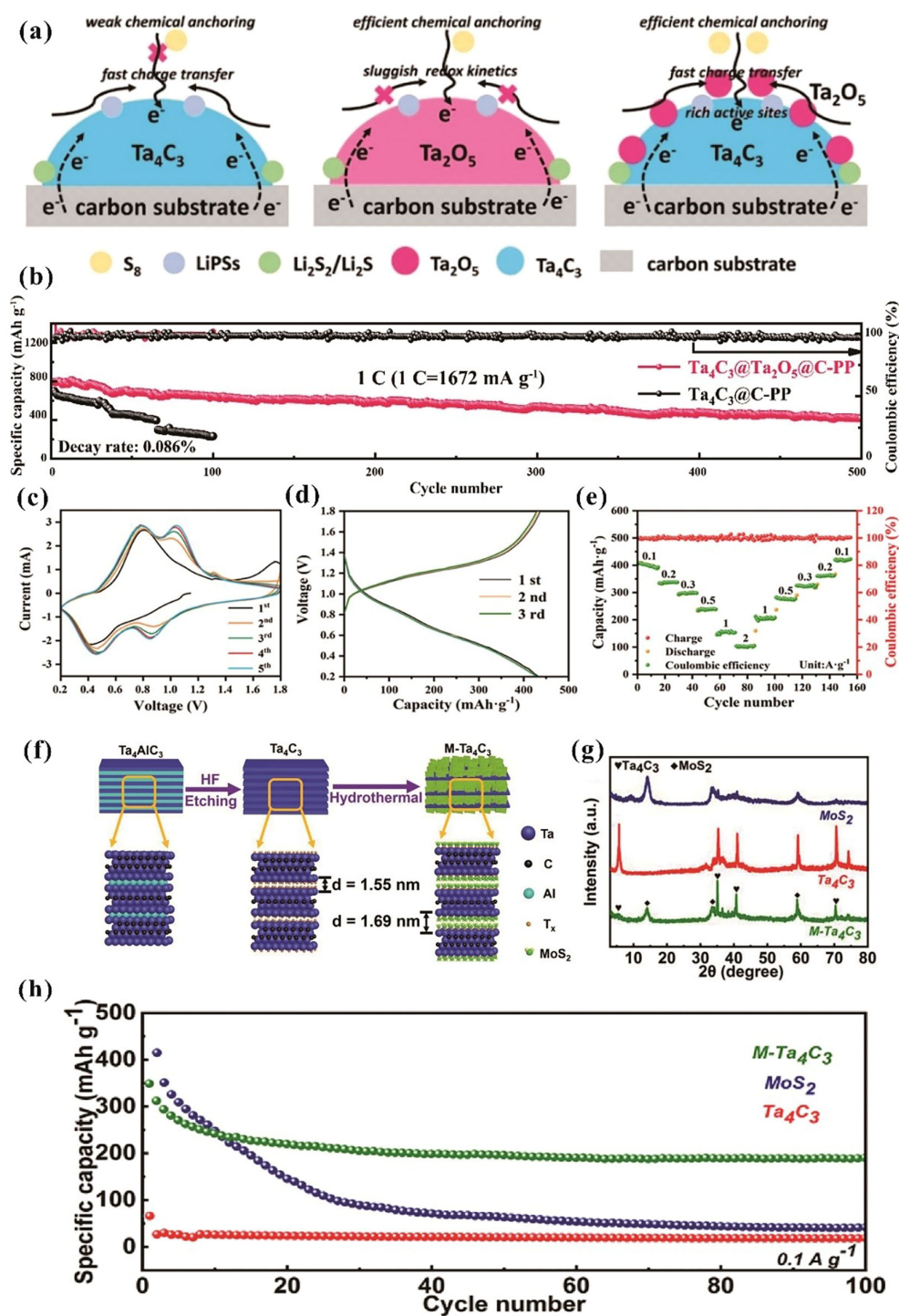


Figure 5. (a) Schematic illustration of the synthesis for $\text{Ta}_4\text{C}_3\text{-Ta}_2\text{O}_5$ heterostructure architectures. (b) Electrochemical cycling performance of $\text{Ta}_4\text{C}_3\text{-Ta}_2\text{O}_5\text{@C-PP}$ and $\text{Ta}_4\text{C}_3\text{@C-PP}$ cells over 500 cycles at 1 C. Permission granted for reproduction [9]. Copyright (2023), Elsevier. (c) CV curves of $\text{VO}_2(\text{B})\text{@Ta}_4\text{C}_3$ for the first five cycles, obtained at a scan rate of 1 mV/s. (d) GCD profiles at a current density of 0.1 A/g for the initial three cycles of the $\text{VO}_2(\text{B})\text{@Ta}_4\text{C}_3$ composite. (e) Rate performance of $\text{VO}_2(\text{B})\text{@Ta}_4\text{C}_3$ cathode across current densities ranging from 0.1 to 2 A/g. Permission granted for reproduction [26]. Copyright (2023), American Chemical Society. (f) A schematic representation of the synthetic process for $\text{MoS}_2\text{-Ta}_4\text{C}_3$ ($\text{M-Ta}_4\text{C}_3$). (g) The XRD patterns of MoS_2 , Ta_4C_3 , and $\text{M-Ta}_4\text{C}_3$. (h) The cycling stability of MoS_2 , Ta_4C_3 , and $\text{M-Ta}_4\text{C}_3$ at a current density of 0.1 A/g. Permission granted for reproduction [8]. Copyright (2021), Elsevier.

5.1.2. Zinc Ion Batteries

Zinc ion batteries (ZIBs) exhibit multiple advantages, including low-cost zinc anodes, high theoretical capacity ($820 \text{ mAh}\cdot\text{g}^{-1}$), and low equilibrium potential (-0.76 V), coupled with inherent safety from aqueous electrolytes, making them significant promise for both grid storage and electric vehicles. However, ZIBs face critical challenges, including vanadium oxide cathode dissolution, structural instability during Zn^{2+} intercalation, and rapid capacity fading. $\text{Ta}_4\text{C}_3\text{T}_x$ MXene exhibits superior electrical conductivity, mechanical stability, and a unique electronic structure compared to conventional MXenes, enabling it to serve as an ideal conductive substrate for cathode of ZIBs. The research work by Liu et al. shows that Ta_4C_3 MXene serves as a good substrate for growing vanadium metal-organic framework (V-MOF) [26]. The introduction of Ta_4C_3 modulated the phase evolution of V-MOF toward $\text{VO}_2(\text{B})$ instead of V_2O_5 , resulting in a 3D network cross-linked structure with superior electrochemical performance. This $\text{VO}_2(\text{B})@\text{Ta}_4\text{C}_3$ composite effectively reduces the Zn^{2+} diffusion barrier to 0.34 eV , outperforming both V_2O_5 (0.70 eV) and $\text{VO}_2(\text{B})$ (0.51 eV). Figure 5c illustrates the cyclic voltammetry (CV) curves of the $\text{VO}_2(\text{B})@\text{Ta}_4\text{C}_3$ cathode, obtained at a scan rate of 1 mV/s over a voltage range spanning from 0.2 V to 1.8 V , revealing excellent reversibility in the Zn^{2+} insertion/extraction processes, as evidenced by the consistent peak positions observed over multiple cycles, which confirms the $\text{VO}_2(\text{B})@\text{Ta}_4\text{C}_3$ composite's high structural stability and efficient electrochemical performance. As shown in Figure 5d, the GCD profiles measured at a current density of 0.1 A/g demonstrate an initial discharge capacity of 437 mAh/g for the $\text{VO}_2(\text{B})@\text{Ta}_4\text{C}_3$ cathode. Figure 5e illustrates the rate capability of the $\text{VO}_2(\text{B})@\text{Ta}_4\text{C}_3$ cathode material across a wide range of current densities, spanning from 0.1 to 2 A/g , exhibiting excellent capacity retention and recovery when returning to lower current densities. The consistently high Coulombic efficiency, approaching almost 100% throughout the cycling process, underscores the excellent electrochemical reversibility and robust structural stability of the $\text{VO}_2(\text{B})@\text{Ta}_4\text{C}_3$ cathode, demonstrating superior electrochemical reversibility for ZIBs applications.

5.1.3. Sodium Ion Capacitors

Sodium ion capacitors offer a cost-effective and resource-abundant alternative to lithium-ion systems. MoS_2 nanosheets demonstrate a theoretical capacity of 670 mAh/g for Na^+ storage [40]. Yet, the electrochemical performance of MoS_2 nanosheets is significantly hindered by agglomerative stacking, cycling-induced mechanical degradation, low conductivity, and kinetically limited Na^+ intercalation processes. Liu et al. first employed $\text{Ta}_4\text{C}_3\text{T}_x$ MXene in Na^+ storage applications and found that the $\text{Ta}_4\text{C}_3\text{T}_x$ MXene can address critical challenges by spatially confined growth of 2D MoS_2 nanosheets both on the surface and within the interlamellar of layered $\text{Ta}_4\text{C}_3\text{T}_x$ MXene [8]. The accordion-like architecture of $\text{Ta}_4\text{C}_3\text{T}_x$ MXene functions as both a conductive scaffold and physical constraint matrix, simultaneously mitigating MoS_2 nanosheet aggregation and volume expansion while enhancing electron conduction (Figure 5f). The XRD pattern (Figure 5g) shows a (002) plane of $\text{MoS}_2\text{-Ta}_4\text{C}_3$ shifting from 5.7° to 5.3° compared to pristine Ta_4C_3 , indicating an enlarged interlayer spacing from 1.55 nm to 1.69 nm due to the pillar effect of intercalated MoS_2 nanosheets. The Na^+ ion capacitor obtained by using 2D $\text{MoS}_2/\text{Ta}_4\text{C}_3\text{T}_x$ as anode and active carbon as cathode demonstrates excellent energy storage capabilities, achieving 87.6 Wh kg^{-1} specific energy density alongside an impressive 3937.3 W kg^{-1} power density. Figure 5h shows the cycling stability of MoS_2 , Ta_4C_3 , and $\text{MoS}_2\text{-Ta}_4\text{C}_3$ at 0.1 A/g over 100 cycles, revealing superior electrochemical performance of $\text{MoS}_2\text{-Ta}_4\text{C}_3$ with a high capacity of 218.8 mAh g^{-1} after 100 cycles. This significantly surpasses pure MoS_2 (fading to 41.2 mAh g^{-1}) and Ta_4C_3 (18.6 mAh g^{-1}), highlighting the synergistic enhancement achieved by employing Ta_4C_3 in Na^+ storage.

5.2. Energy Conversion and Environmental Remediation

5.2.1. Hydrogen Production

Hydrogen is a clean and sustainable energy source with zero emissions and high energy density, emerged as a promising substitute for traditional fossil fuels in sustainable energy systems. Electrochemical water splitting represents a highly viable approach for scalable hydrogen generation. The research work of Wu et al. demonstrates a one-step synthesis of 2D Ta_2CS_2 with ordered sulfur termination (Figure 6a), exhibiting superior conductivity and bifunctional catalytic activity (hydrogen evolution reaction, HER) for overall water splitting in 1 M KOH [41]. The layered Ta_2CS_2 was exfoliated into ultrathin two-dimensional nanosheets ($\text{Ta}_2\text{CS}_2\text{-E}$) using N,N-dimethylformamide (DMF) (Figure 6b). The polarization curves depicted in Figure 6c show that the HER performance of $\text{Ta}_2\text{CS}_2\text{-E}$ is close to that of conventional Pt/C material. $\text{Ta}_2\text{CS}_2\text{-E}$ demonstrates an overpotential of 73 mV at $10 \text{ mA}/\text{cm}^2$, approaching commercial Pt/C (44 mV). $\text{Ta}_2\text{CS}_2\text{-E}$ demonstrates a Tafel slope that is comparable to that of Pt/C among various catalysts (Figure 6d), indicating its effectiveness in promoting the HER. The long-term stability performance of $\text{Ta}_2\text{CS}_2\text{-E}$ indicates that it exhibits nearly 100% retention of current density, maintaining a value of $10 \text{ mA}/\text{cm}^2$ at an overpotential of 73 mV (Figure 6e) over a period of 48 h. This study demonstrates $\text{Ta}_2\text{CS}_2\text{-E}$ as an excellent catalyst, offering good potential for future electrochemical water splitting.

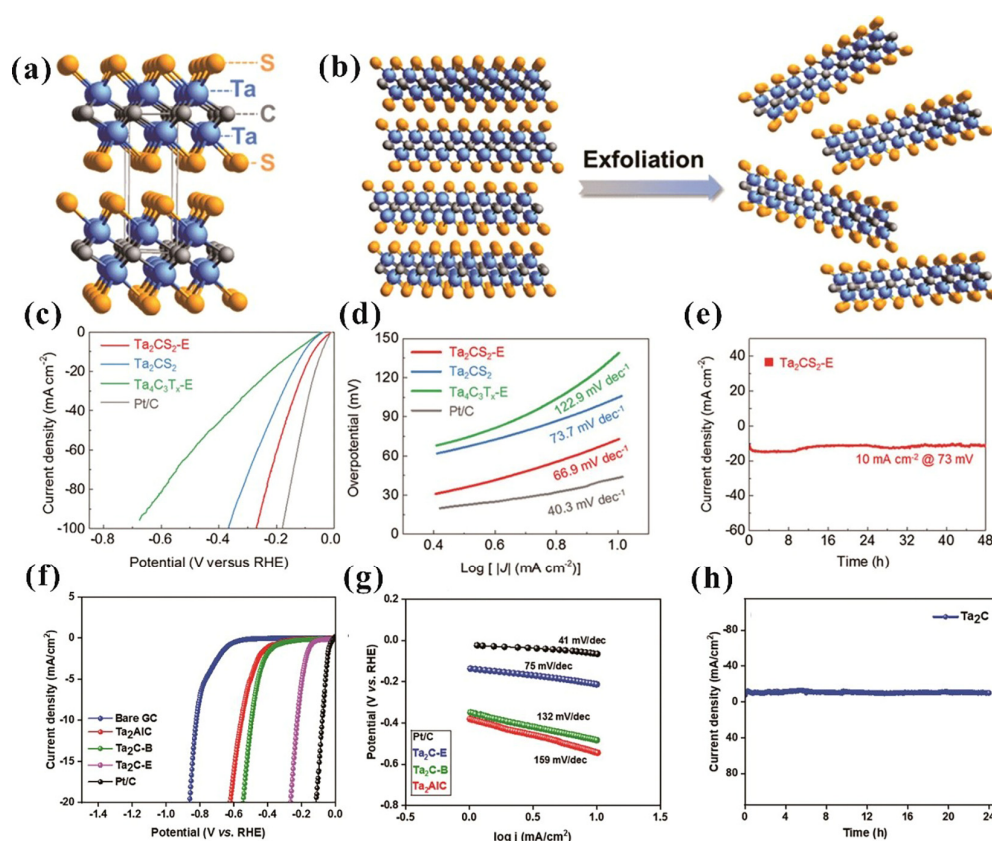


Figure 6. (a) Crystal structure of Ta_2CS_2 . (b) The schematic illustration of exfoliation route for generating $\text{Ta}_2\text{CS}_2\text{-E}$ nanosheets. (c) HER polarization curves and (d) Tafel slopes of $\text{Ta}_2\text{CS}_2\text{-E}$ compared with other samples. (e) Stability study of $\text{Ta}_2\text{CS}_2\text{-E}$ at an overpotential of 73 mV. Permission granted for reproduction [41]. Copyright (2021), Wiley-VCH. (f) HER polarization curves and (g) Tafel slopes of $\text{Ta}_2\text{C}/\text{E}$ compared with other samples. (h) Time-dependent current density curves of $\text{Ta}_2\text{C}/\text{E}$. Permission granted for reproduction [10]. Copyright (2021), Elsevier.

In another research work, Vijayaprabakaran et al. synthesized 2D Ta₂C via a fluorine-free etching method and found that Ta₂C MXene served as an efficient electrocatalyst for both HER and nitro compound reduction [10]. The LSV curve reveals that (Ta₂C-E) MXene exhibits excellent HER kinetics in 0.5 M H₂SO₄, demonstrating performance comparable to that of Pt-C catalysts (Figure 6f). The Tafel slopes of the electrocatalysts were determined to be 75 mV/dec for Ta₂C-E MXene and 44 mV/dec for Pt-C (Figure 6g). Notably, the Tafel slope of Ta₂C-E MXene is closely aligned with that of Pt-C, suggesting its favorable HER kinetics. The chronoamperometric study (Figure 6h) revealed that Ta₂C-E MXene exhibited remarkable stability for 24 h under HER conditions without any loss of activity, alongside its enhanced electrocatalytic performance, evidenced by a lower onset potential and higher cathodic peak current in 0.5 M H₂SO₄. These research findings indicate that Ta₂C is a promising candidate for efficient electrocatalytic hydrogen production.

5.2.2. Photo/Electrothermal Conversion

In recent years, significant attention has been focused on developing multifunctional photothermal/electrothermal conversion materials to address critical environmental and health challenges, such as freshwater scarcity and tumor treatment. Liu et al. fabricated novel Ta₄C₃T_x/graphene aerogel composites via a hydrothermal method followed by freeze-drying, which exhibit superior photo/electrothermal conversion performance and multifunctional applicability [42]. As depicted in the inset of Figure 7a, Ta₄C₃T_x/graphene aerogel (TGA-6) appears as a black cylinder with an extremely low density of 24.6 mg/cm³. Its microporous network structure, clearly revealed in the FESEM images, enhances sunlight scattering and optimizes solar energy utilization. The photothermal performance of Ta₄C₃T_x/graphene aerogel was tested under 1 sun simulated sunlight, showing the sample reached 85.3 °C in 3 s and up to 90.2 °C in 50 s, with temperatures stabilizing after 1 min (Figure 7b). Figure 7c illustrates the relationship between the surface temperature and irradiation time, demonstrating its rapid photothermal conversion capability. By utilizing its photo/electrothermal properties, this Ta₄C₃T_x/graphene aerogel can be successfully applied in seawater steam generation, thermal therapy, deicing, and the absorption of high-viscosity oil. The enhanced photothermal conversion efficiency of the Ta₄C₃T_x/graphene aerogel composites can be attributed to the synergistic effects between Ta₄C₃T_x and graphene aerogel, where the porous structure of graphene aerogel acts as light-trapping caves for maximizing solar energy utilization through multiple reflections and scattering, while Ta₄C₃T_x, with its superior conductivity and stability in air, further improves the electrical conductivity and sunlight absorption capability of the composite. Additionally, the hierarchical porous structure facilitates water transport and enhances overall solar energy utilization efficiency.

5.2.3. Pollutant Degradation

Environmental pollution is a significant challenge, especially concerning wastewater that contains dyes and antibiotics, which negatively impacts ecosystems and health. Zhang et al. developed innovative NH₂-MIL-88B/Ta₄C₃T_x/graphene aerogels with remarkable capabilities for photocatalytic applications and thermal energy storage using solar energy [43]. By utilizing a hydrothermal method and subsequent freeze-drying process, the MOF material NH₂-MIL-88B was successfully integrated with Ta₄C₃T_x to prepare the NH₂-MIL-88B/Ta₄C₃T_x/graphene composite. The combination of NH₂-MIL-88B as a photocatalyst, Ta₄C₃T_x as a co-catalyst and adsorbent, and graphene aerogel provided a 3D porous structure that generates a significant synergistic effect, leading to superior physicochemical properties of the composite. The NH₂-MIL-88B/Ta₄C₃T_x/graphene composite exhibited superior degradation efficiencies for Congo red (GR), methylene blue (MB),

and tetracycline hydrochloride (TC-HCl) (Figure 7d–f). Under visible light irradiation, $\text{NH}_2\text{-MIL-88B}$ generates electron-hole pairs owing to its 1.69 eV bandgap, and the electrons transfer to reduced graphene oxide and $\text{Ta}_4\text{C}_3\text{T}_x$ to form a conductive network that suppresses charge recombination. Simultaneously, holes on $\text{NH}_2\text{-MIL-88B}$ produce hydroxyl radicals ($\bullet\text{OH}$) by reacting with OH^- , and electrons on graphene/MXene generate superoxide radicals ($\bullet\text{O}_2^-$) through oxygen adsorption, leading to the mineralization of pollutants into CO_2 and H_2O (Figure 7g). This study demonstrates that $\text{Ta}_4\text{C}_3\text{T}_x$ MXene exhibits significant promise for photocatalytic pollutant degradation.

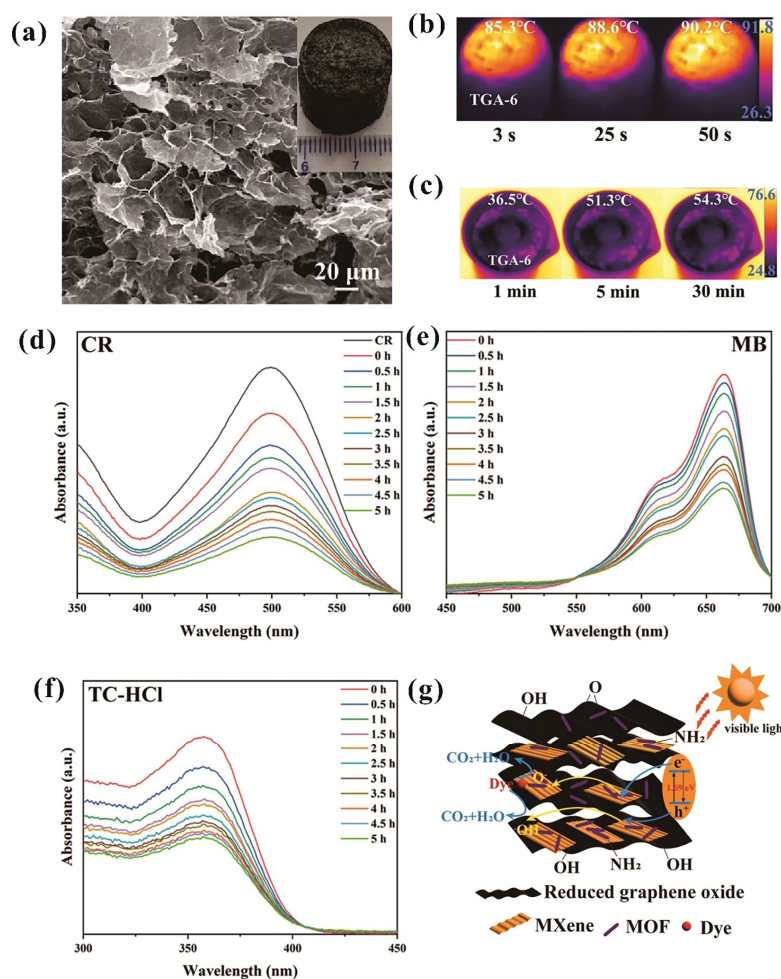


Figure 7. (a) SEM images of $\text{Ta}_4\text{C}_3\text{T}_x$ /graphene aerogel. (b,c) Thermal infrared imaging and surface temperature analysis of $\text{Ta}_4\text{C}_3\text{T}_x$ /graphene aerogel composites in the dry state at varying time intervals. Permission granted for reproduction [42]. Copyright (2024), Elsevier. UV–visible absorption spectra of (d) CR, (e) MB, and (f) TC-HCl with respect to irradiation time, demonstrating the photocatalytic degradation activities of $\text{NH}_2\text{-MIL-88B}/\text{Ta}_4\text{C}_3\text{T}_x$ /graphene. (g) Photocatalytic degradation mechanism of dye/drug on $\text{NH}_2\text{-MIL-88B}/\text{Ta}_4\text{C}_3\text{T}_x$ /graphene under visible light illumination. Permission granted for reproduction [43]. Copyright (2025), Elsevier.

5.3. Detection and Sensing

5.3.1. SERS

Surface-enhanced Raman scattering (SERS) is a powerful spectroscopic tool distinguished by its sensitivity, specificity and rapid detection, making it ideal for biological and environmental applications. Wang et al. synthesized a Ta_4C_3 MXene/gold nanostar hybrid as a SERS substrate, as shown in Figure 8a [15]. Figure 8b demonstrates that Au nanostars (AuNSs) are attached to the Ta_4C_3 MXene surface, ensuring both the effective attachment

of AuNSs to the two-dimensional substrate and the interaction between adjacent nanoparticles, thereby generating SERS hot spots. UV–vis spectroscopy reveals the blue shift in absorption peaks of AuNSs when combined with Ta₄C₃ MXene (Figure 8c), indicating tighter connections in the composite structure. The Ta₄C₃ MXene/AuNSs hybrids substrate exhibits superior SERS performance for detecting 4-aminothiophenol (PATP) molecules compared to individual components (Au nanostars or Ta₄C₃ MXene) (Figure 8d). The Ta₄C₃ MXene facilitates charge transfer between its 2D electron gas structure and adsorbed PATP molecules via molecular orbital interactions, amplifying Raman signals through chemical enhancement. Moreover, the high specific surface area and surface hydroxyl/carboxyl groups of Ta₄C₃ MXene enhance molecular adsorption capacity, accumulating more analyte molecules on the composite substrate and boosting detection sensitivity. Figure 8e presents the Raman spectra of Ta₄C₃ MXene/AuNSs used for detecting various concentrations of PATP, demonstrating that the detection limit can reach as low as 10^{−9} M. In another study by Lan et al., it was demonstrated that 2D Ta₄C₃ nanosheet by itself is a superior material for SERS sensing [14], removing the dependence on noble metals (Figure 8f). A 2D Ta₄C₃ nanosheet exhibited excellent detection performance for both Rhodamine 6G (R6G) and crystal violet (CV), with detection limits of 1 × 10^{−7} M for R6G (Figure 8g) and 1 × 10^{−6} M for CV (Figure 8h), demonstrating its high sensitivity in SERS measurements.

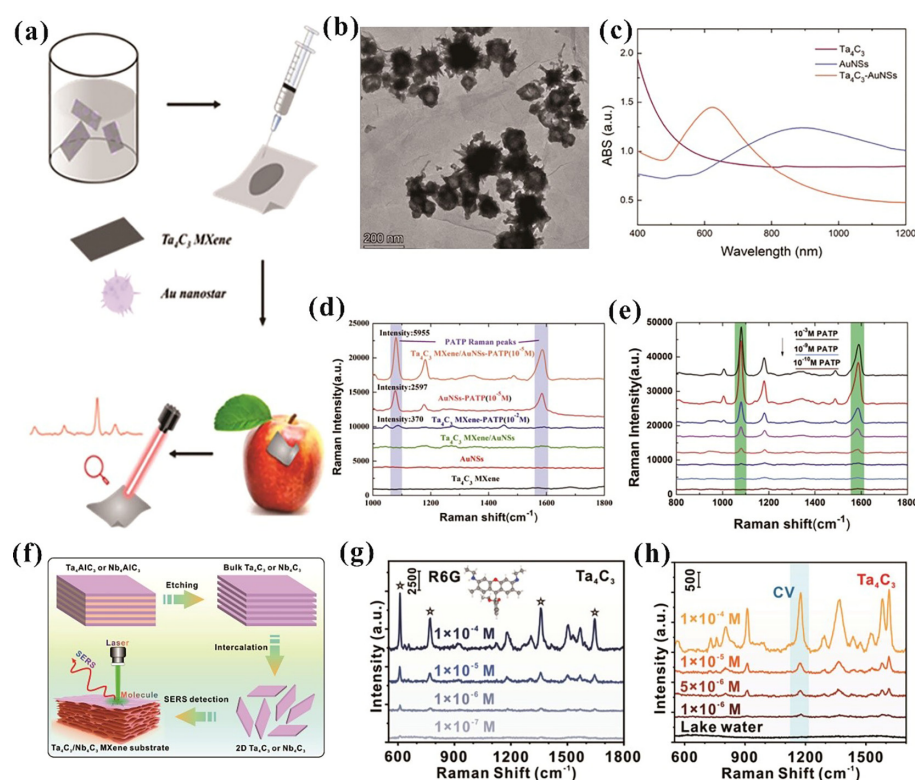


Figure 8. (a) Preparation of 2D Ta₄C₃ MXene/ANSs composites as SERS substrates. (b) TEM images of Ta₄C₃ MXene/AuNSs composites. (c) UV–vis absorption spectra of Ta₄C₃ MXene, AuNSs, and the Ta₄C₃ MXene/AuNSs composite structure. (d) Raman spectra of Ta₄C₃ MXene, AuNSs, Ta₄C₃ MXene/AuNSs, Ta₄C₃ MXene/AuNSs with 10^{−5} M PATP, AuNSs with 10^{−5} M PATP, and Ta₄C₃ MXene with 10^{−2} M PATP. (e) Raman spectra of Ta₄C₃ MXene/AuNSs for detecting various concentrations of PATP. Permission granted for reproduction [15]. Copyright (2024), American Chemical Society. (f) Schematic representation of the synthesis and SERS application for 2D Ta₄C₃ and Nb₄C₃ nanosheet. (g) Raman spectra of R6G with concentrations ranging from 10^{−4} to 10^{−7} M adsorbed on Ta₄C₃. (h) Raman spectra of CV with concentrations ranging from 10^{−4} to 10^{−6} M adsorbed on Ta₄C₃. Permission granted for reproduction [14]. Copyright (2024), American Chemical Society.

5.3.2. Gas Sensors

Tantalum Carbide MXenes can be utilized as efficient gas sensors, utilizing their unique properties for sensitive and selective detection of various gas molecules. The gas-sensing performance of tantalum carbide MXenes is mainly driven by the chemisorption of gases and the interaction with surface functional groups. Kong et al. fabricated gas sensors by drop-casting monolayers of $\text{Ta}_4\text{C}_3\text{T}_x$ onto interdigital electrodes, which exhibited high sensitivity and selectivity to ammonia at room temperature with a low detection limit of 0.72 ppm. TEM in Figure 9a reveals that few-layer or monolayer $\text{Ta}_4\text{C}_3\text{T}_x$ forms a relatively uniform film without obvious defects. Figure 9b shows the resistance change of the $\text{Ta}_4\text{C}_3\text{T}_x$ sensor during recovery at room temperature for NH_3 concentrations ranging from 65 to 325 ppm. The cyclability of the sensor was measured at 100 ppm ammonia over three cycles, as shown in Figure 9c, where the consistent response amplitude indicates good repeatability of the sensor [12].

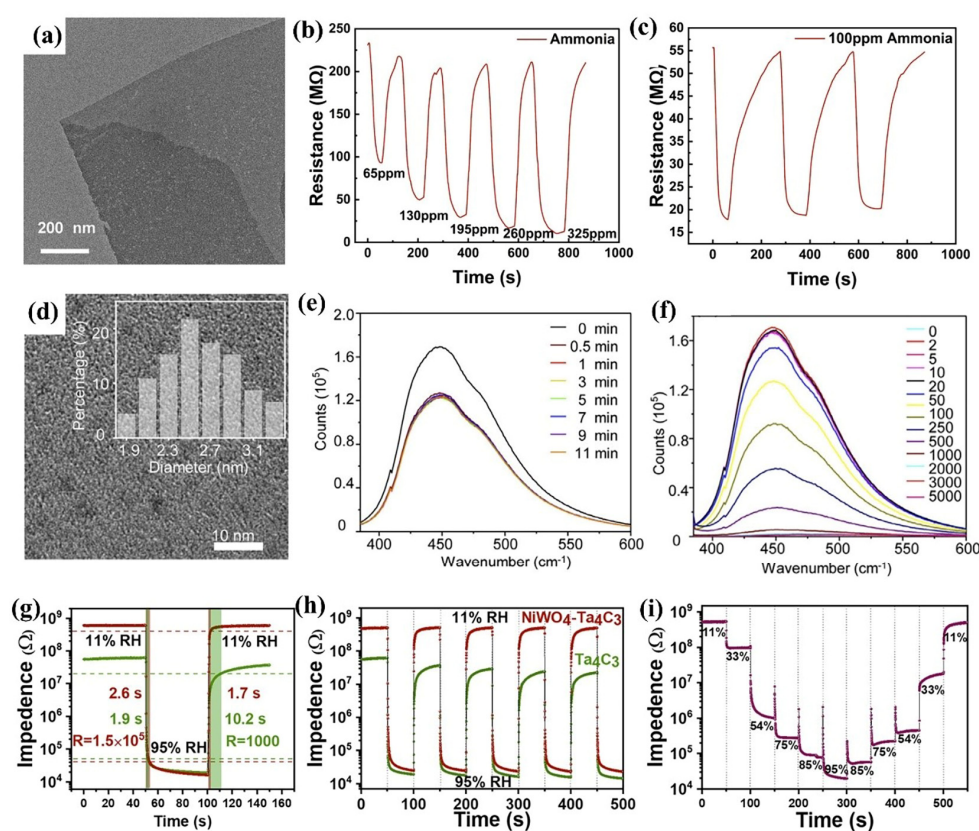


Figure 9. (a) TEM of $\text{Ta}_4\text{C}_3\text{T}_x$ nanosheet. (b) Dynamic response curves of $\text{Ta}_4\text{C}_3\text{T}_x$ to NH_3 concentrations ranging from 65 to 325 ppm. (c) Repeatability test of $\text{Ta}_4\text{C}_3\text{T}_x$ at 100 ppm NH_3 over multiple cycles. Permission granted for reproduction [12]. Copyright (2024), Elsevier. (d) TEM of N-MQDs. (e) Time-dependent fluorescence quenching of N-MQDs by 100 $\mu\text{mol/L}$ Fe^{3+} . (f) PL emission profiling of N-MQDs with different concentrations ($\mu\text{mol/L}$) of Fe^{3+} . Permission granted for reproduction [44]. Copyright (2022), Elsevier. (g) The response and recovery durations, along with the response levels, for the $\text{NiWO}_4\text{-Ta}_4\text{C}_3$ material (red curve) and Ta_4C_3 MXene nanosheet (green curve) humidity sensors. (h) Continuous working stability of the $\text{NiWO}_4\text{-Ta}_4\text{C}_3$ (red curve) and Ta_4C_3 MXene (green curve) humidity sensors. (i) Resistance values of $\text{NiWO}_4\text{-Ta}_4\text{C}_3$ humidity sensor at different humidities. Permission granted for reproduction [13]. Copyright (2023), American Chemical Society.

5.3.3. Ion Detection

Li et al. developed an innovative synthesis strategy to prepare nitrogen-doped Ta_4C_3 quantum dots (N-MQDs) with a uniform particle size of 2.60 nm (Figure 9d), achieving re-

markable fluorescence quantum yields [44]. The synthesized N-MQDs exhibit outstanding photoluminescent (PL) characteristics, emitting intense blue fluorescence with a remarkably high quantum yield of 23.4%. The abundant -NH_2 and -OH groups, along with N and O atoms on N-MQDs surfaces, provide a strong electron absorbing capability that effectively passivates surface defects. The N-MQDs exhibit good functionality as an advanced fluorescent nanosensor, demonstrating highly selective Fe^{3+} detection capability. The adsorption of Fe^{3+} induces efficient electron transfer, accelerating electron/hole recombination on surface of N-MQDs, thereby altering electronic state and enabling selective fluorescence quenching for sensing applications. The rapid fluorescence quenching of N-MQDs within 0.5 min upon Fe^{3+} addition (Figure 9e) demonstrates their high detection efficiency, with a significant signal reduction at 100 $\mu\text{mol/L}$ and a detection limit as low as 2 $\mu\text{mol/L}$ (Figure 9f), confirming strong potential of N-MQDs for Fe^{3+} sensing.

5.3.4. Humidity Sensing

Liu et al. reported that a humidity sensor utilized accordion-like Ta_4C_3 MXene nanosheets as its sensing material, demonstrating excellent performance characterized by ultralow loading, high sensitivity, and fast response/recovery kinetics [13]. First-principles calculations demonstrate that Ta_4C_3 MXene nanosheets exhibit good water molecule adsorption capabilities, with an adsorption energy reaching 2.01 eV, substantially exceeding those observed for NiWO_4 (0.37 eV) and Ti_3C_2 (1.08 eV). Moreover, Ta_4C_3 MXene offers a high specific surface area, which accelerates the initial adsorption process. NiWO_4 nanoparticles enhance the desorption performance of water molecules and the linear response characteristics of the composite material. The hybrid structure combines the high electrical conductivity of Ta_4C_3 MXene with the stability of NiWO_4 , resulting in superior humidity sensing capabilities of the composite material. As illustrated in Figure 9g, the resistance variations of both the $\text{NiWO}_4\text{-Ta}_4\text{C}_3$ and Ta_4C_3 MXene nanosheet-based humidity sensors are presented within the relative humidity (RH) range of 11% to 95%. Figure 9h illustrates the repeatability of $\text{NiWO}_4\text{-Ta}_4\text{C}_3$ and Ta_4C_3 MXene nanosheet humidity sensors over 5 cycles between 11% and 95% RH, showing that the $\text{NiWO}_4\text{-Ta}_4\text{C}_3$ sensor maintains stable performance with little change, whereas the Ta_4C_3 MXene sensor fails to retain its initial response due to incomplete desorption of water molecules within the given time. Figure 9i presents the resistance values of the $\text{NiWO}_4\text{-Ta}_4\text{C}_3$ humidity sensor at relative humidities of 11%, 33%, 54%, 75%, 85%, and 95%, demonstrating the excellent response performance of the sensors across different humidity levels. This study establishes Ta_4C_3 MXene as a promising humidity sensor material.

5.3.5. Piezoresistive Sensing

The continuous monitoring of human physiological parameters via high-precision sensing technologies has garnered considerable research interest. Ta_4C_3 nanosheets exhibit superior properties for piezoresistive sensing applications, including excellent electrical conductivity, good mechanical stability, abundant functional groups facilitating sponge integration, and enhanced air stability compared to conventional MXene materials, collectively enabling high-performance, durable pressure sensors suitable for diverse environmental conditions. According to the research of Wu et al., Ta_4C_3 nanosheet/melamine sponge piezoresistive sensors were successfully fabricated via the integration of etching-intercalation and dipping-drying techniques [30]. This sensor exhibits superior performance metrics, such as a high sensitivity of 4.01 kPa^{-1} , a broad linear range of 0.018–12.06 kPa, a low detection limit of 18.5 Pa, and rapid response/recovery times of 35.4/27.88 ms. With their excellent stability and durability, these sensors are well-suited to real-time physi-

ological signal monitoring and have the potential for wireless detection of human and robotic motions.

5.4. Advantages over Ti-Based MXene

Ta-based MXenes are a newer member of the MXene family, exhibiting unique advantages in terms of structure and functionality compared to common titanium (Ti)-based MXenes, such as $\text{Ti}_3\text{C}_2\text{T}_x$. For example, according to Lin et al.'s report, the Ta_4C_3 nanosheets demonstrated an high photothermal conversion efficiency (η) of 44.7%, outperforming Ti_3C_2 nanosheets (30.6%) [25]. Stavrou et al. studied ultrafast nonlinear optical (NLO) properties and carrier dynamics of $\text{Ta}_4\text{C}_3\text{T}_x$. They found that $\text{Ta}_4\text{C}_3\text{T}_x$'s NLO response surpasses $\text{Ti}_3\text{C}_2\text{T}_x$, attaining exceptionally high third-order susceptibility ($\chi^{(3)}$) values on the order of 10^{-13} esu [45]. Guo et al. investigated the $\text{Ta}_{n+1}\text{C}_n$ as anode materials for rechargeable metal ion batteries by DFT. The findings reveal that $\text{Ta}_{n+1}\text{C}_n$ MXenes exhibit outstanding adsorption capabilities and remarkable electronic conductivities when it comes to accommodating Li, Na, K, Mg, and Ca atoms. Moreover, the presence of ultra-low diffusion barriers for alkali metal ions suggests that $\text{Ta}_{n+1}\text{C}_n$ MXenes hold significant potential for achieving high-performance characteristics, particularly in the context of ultra-fast charging and discharging processes [46]. Rafieerad et al. demonstrated a fluorine-free exfoliation method for synthesizing $\text{Ta}_4\text{C}_3\text{T}_x$ MXene-tantalum oxide. This material exhibits better biocompatibility than other MXene materials, making it highly suitable for implantable bioelectronic devices and tissue engineering applications [11]. Liu et al. successfully fabricated a NiWO_4 - Ta_4C_3 -based humidity sensor, which demonstrated superior performance compared to the humidity sensors prepared with Ti_3C_2 MXene, NiWO_4 , and NiWO_4 - Ti_3C_2 [13]. For a comparison highlighting the superiority of tantalum carbide MXenes, the properties of tantalum carbide MXenes are presented alongside those counterparts (Table 3).

Table 3. Comparison of the properties of tantalum carbide MXenes in various applications.

Material	Properties of Ta-MXene	Ta-MXene's Function	Application	Ref.
$\text{Ta}_4\text{C}_3\text{T}_x$ - Ta_2O_5	Superior electrical conductivity, good mechanical properties	Formation of a robust shielding layer on the Li metal surface to inhibit the growth of Li dendrites	Li-S batteries	[9]
$\text{VO}_2(\text{B})@\text{Ta}_4\text{C}_3$	A high specific surface area, high electrical conductivity	Increases the number of active sites, improve the conductivity and ion diffusion efficiency	ZIBs	[26]
2D Ta_4C_3 supported 2D MoS_2	A larger interlayer spacing	An ideal matrix for constructing a 3D heterostructure	Sodium ion capacitors	[8]
Exfoliated Ta_2CS_2	Excellent conductivity, high specific surface area and the exposed activity	Decreases overpotential	Electrocatalytic HER an OER	[41]
Ta_4C_3 MXene/gold nanostar	High specific surface area, excellent conductivity	Strong adsorption capacity for detection molecules, improved photoelectron transfer	SERS	[15]
Monolayer $\text{Ta}_4\text{C}_3\text{T}_x$	High adsorption energy for ammonia	Strong reactions to ammonia	Ammonia detection	[12]
Ta_4C_3 nanosheet/melamine	Layered nanostructure, impressive mechanical properties, and excellent metallic conductivity	Prolonged sensor lifespan and improved suitability	Piezoresistive Sensors	[30]

5.5. Other Applications

Tantalum carbide MXene demonstrates extensive applicability across multiple advanced technological domains, including energy storage, energy conversion, environmental remediation, detection and sensing, and various other frontier applications. Owing to its tunable physicochemical characteristics and the ability to be hybridized with a variety of other materials, tantalum carbide MXene has emerged as a multifunctional platform material with burgeoning applications in biomedical applications, optics and photonics, as well as nuclear and radiation applications.

Due to its high atomic number ($Z = 73$) and impressive X-ray attenuation coefficient ($4.3 \text{ cm}^2/\text{kg}$ at 100 eV, compared to $1.94 \text{ cm}^2/\text{kg}$ for iodine), tantalum has been identified as a promising candidate for use in CT contrast agents [47,48]. Ta_4C_3 MXene exhibits remarkable photothermal conversion efficiency, surpassing traditional photothermal agents such as Au nanorods, making Ta_4C_3 MXene a promising material for multiple imaging-guided photothermal tumor ablation. Dai et al. modified $\text{MnO}_x/\text{Ta}_4\text{C}_3$ by soybean phospholipid (SP), yielding $\text{MnO}_x/\text{Ta}_4\text{C}_3\text{-SP}$ composites with tumor theranostic capabilities [20]. The Ta_4C_3 demonstrated a photothermal conversion efficiency of 34.9%. Within 10 min, the tumor surface temperature in $\text{MnO}_x/\text{Ta}_4\text{C}_3\text{-SP}$ treated mice increased to around 55°C , as observed via infrared thermal imaging, achieving a level sufficient for effective tumor ablation. Blood and organ function analyses at 30 days post-injection showed no significant differences between the $\text{MnO}_x/\text{Ta}_4\text{C}_3\text{-SP}$ treated groups and the control group, indicating the safety of the composite nanosheet. This research work demonstrates that Ta_4C_3 holds great potential for both photoacoustic imaging and photothermal ablation of tumors. In addition to the application in tumor ablation, excellent photothermal conversion and biocompatibility make tantalum carbide MXene a promising material for therapeutic platforms against antibiotic-resistant infections. According to the report by Wang et al., Ta_4C_3 exhibits remarkable photothermal conversion efficiency, significant reactive oxygen species scavenging abilities, and notable immunomodulatory characteristics [29]. Comprehensive in vitro and in vivo analyses demonstrated the effectiveness of Ta_4C_3 in eradicating methicillin-resistant staphylococcus aureus infections and promoting wound healing.

$\text{Ta}_4\text{C}_3\text{T}_x$ demonstrates excellent potential for optoelectronic applications across a broad spectral range. For example, Dong et al. conducted a theoretical study using DFT-based first-principles calculations to study the influence of surface functionalization on Ta_4C_3 MXene's electronic structure and optical response. The results show that oxidized/hydroxylated Ta_4C_3 variants exhibit significantly enhanced near-infrared absorption compared to bare Ta_4C_3 [18]. Terminated Ta_4C_3 demonstrate broadband near-infrared nonlinear absorption and effective mode-locking at 1044/1557 nm, suggesting potential for optical modulators. Du et al.'s research also demonstrates that Ta_4AlC_3 and Ta_4C_3 possess outstanding nonlinear absorption capabilities in the ultraviolet range, particularly showing remarkable optical limiting performance, making them highly promising materials for optical limiting applications and advancing their potential in photonics and nonlinear optics for laser protection [37].

Owing to their elevated atomic number ($Z = 73$) of Ta element, tantalum carbide MXenes exhibit exceptional potential for nuclear and radiation applications. Ta displays significant γ -ray characteristics within the 67.4–88 keV energy range [24], which makes it an ideal candidate for the fabrication of multifunctional radiation protection materials. Liu et al. developed a flexible, self-healing, thermal-managing, and responsive radiation protection material using $\text{Ta}_4\text{C}_3\text{T}_x$ MXene, hydrogen-terminated phenyl polysiloxane, and polyborosiloxane, which exhibits enhanced tensile strength, high sensitivity, and superior γ -ray attenuation compared to Ta_2O_5 composites, demonstrating the potential of $\text{Ta}_4\text{C}_3\text{T}_x$ MXene in nuclear environments [24]. In another research work of this group, they fabricated

multilayer composites with an interlocked structure through vacuum filtration and layer-by-layer assembly, utilizing $\text{Ta}_4\text{C}_3\text{T}_x$ MXene as the filler, multi-crosslinked elastomers as the matrix, and abrasive cloths as templates to enhance mechanical and attenuation properties [36]. The composites exhibited superior thermal management and radiation protection properties, with a mass attenuation coefficient of $0.927 \text{ cm}^2/\text{g}$ for 59.6 keV γ -rays, demonstrating considerable promise in diverse applications in low-temperature nuclear environments, particularly as wearable radiation protection materials.

6. Summary and Outlook

This review provides summary of the advancing research on tantalum carbide MXenes, with particular focus on Ta_2CT_x and $\text{Ta}_4\text{C}_3\text{T}_x$. The synthesis, properties, and applications have been explored across various fields, highlighting their remarkable potential in energy storage, energy conversion, sensing, biomedicine, and so on.

The production of tantalum carbide MXenes is mainly achieved through a top-down etching process that has evolved from conventional HF-etching methods towards more eco-friendly alternatives. Fluorine-free synthesis methods, including KOH and HCl etching, have emerged as viable alternatives, addressing safety challenges and environmental concerns simultaneously. The employment of advanced exfoliation techniques involving intercalants like TMAOH, TPAOH, and TBAOH has facilitated the synthesis of few-layer and monolayer tantalum carbide MXenes with enlarged interlayer spacing, thereby considerably improving their functional properties.

The intrinsic properties of tantalum carbide MXenes highlight their remarkable potential. Theoretical and experimental studies confirm their metallic conductivity, adjustable electronic structures. Their optical behaviors extend across the ultraviolet to the infrared spectrum, exhibiting notable nonlinear optical responses and efficient photothermal conversion capabilities. Additionally, the surface chemistry of Ta-based MXenes, particularly their terminal functional groups, influences their overall physicochemical behavior and performance.

The range of applications for tantalum carbide MXenes continues to grow rapidly. Within energy storage, they showcase excellent electrochemical behavior across multiple battery systems and capacitors, offering high capacity, excellent rate performance, and outstanding cycling stability. Their catalytic activity toward HER demonstrates promising efficiency towards energy conversion. The sensing capabilities of tantalum carbide MXenes are highly versatile, covering gas detection, humidity sensing, and SERS, with detection limits reaching trace amount. Photothermal properties are utilized in biomedical applications like cancer theranostics and wound healing. Emerging applications further include nonlinear optics for laser protection radiation shielding and so on.

Currently, the exploration of tantalum carbide MXenes is still in the early stages. They still face insufficient structural stability, primarily manifested in the tendency of surface terminal groups (-O, -F, -OH) to dissociate in oxidizing environments. This leads to the degradation of their layered structure, along with a gradual decay in conductivity and optical performance over time, thereby limiting their long-term reliability in optoelectronic devices. Moreover, breakthroughs in efficient, environmentally friendly, and low-cost large-scale preparation techniques remain unrealized. Several issues related to synthesis, properties, and practical applications should be addressed in order to fully unlock their potential. Synthetic approaches require ongoing optimization to develop scalable and environmentally sustainable production methods. Exploring alternative etching techniques beyond conventional fluorine-based routes is a crucial research focus, as it may facilitate industrial-scale synthesis while reducing environmental impact. Precise regulation of surface termination groups remains of importance, as these groups profoundly affect the

functional attributes of tantalum carbide MXenes and dictate their performance across various applications. The integration of computational modeling with advanced characterization methods will remain critical in understanding the atomic-scale mechanisms behind their excellent performance. The integration of tantalum carbide MXenes with other functional materials into composite materials represents a promising research direction. Combining tantalum carbide MXenes with other substances such as metal oxides, chalcogenides, and polymers can synergistically improve performance attributes while addressing the limitations of individual components.

In summary, tantalum carbide MXenes represent a high-potential group of 2D materials, distinguished by their extraordinary properties and versatile applications. Their unique electronic, mechanical, optical, and chemical properties, alongside customizable surface chemistry, establish them as pivotal components for advancing next-generation energy, environmental, biomedical, and optics technologies. Ongoing studies aimed at optimizing synthesis strategies, improving structural designs, and customizing properties for specific purposes will further unlock their full potential.

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