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PERSPECTIVE

Insights into MXene-Based Electrocatalysts for the Oxygen Evolution Reaction

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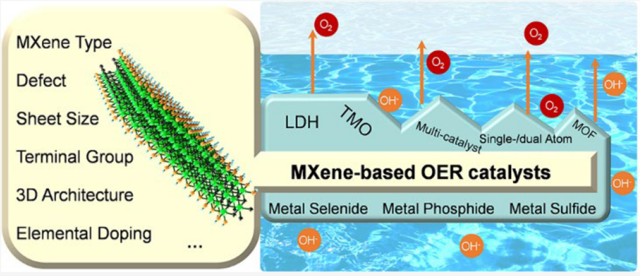

ABSTRACT: **MXenes, a family of two-dimensional transition metal carbides, nitrides, and carbonitrides, have emerged as promising materials for energy storage and conversion. Their hydrophilicity, metallic conductivity, and solution processability make them suitable for catalytic applications. However, challenges such as structural instability, limited active sites, and complex surface chemistry hinder their practical use. Recent efforts have focused on enhancing MXene-based catalysts for the oxygen evolution reaction (OER) through structural engineering and hybridization with layered double hydroxides (LDHs) and transition metal oxides (TMOs). This Perspective summarizes key developments in understanding the intrinsic properties of MXenes and their impact on catalytic performance. Moreover, mechanistic insights, ongoing challenges, and opportunities for the rational design of multifunctional MXene hybrids are highlighted. Addressing these fundamental issues will be essential for unlocking the full potential of MXenes in sustainable energy conversion technologies.**

Since the first report on $Ti_3C_2T_x$ in 2011, the family of two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides, known as MXenes, has expanded tremendously. MXenes possess a general formula of $M_{n+1}X_nT_x$, where M represents transition metal, X denotes carbon or nitrogen sites, n ranges from 1 to 4, and T_x corresponds to surface terminations (with variable x) attached to the outer transition metal layers (Figure 1a).[1] Recently, MXenes have attracted significant attention in electrocatalysis due to their high surface area, tunable electronic properties, exceptional electrical conductivity and abundant active sites arising from rich terminal groups. These unique characteristics make MXenes highly promising candidates for modification of the physicochemical properties, such as surface wettability and reactant accessibility in electrocatalytic processes. Moreover, their versatile surface chemistry and layered morphology offer valuable opportunities for interfacial engineering in composite or hybrid catalysts, thereby enabling further enhancement of the catalytic performance. MXenes can be synthesized either as multilayer flakes or particles (ml-MXene) or as delaminated single-layer sheets (d-MXene).[2−4] Both ml-MXene and d-MXene serve as effective substrates with distinct morphologies and interlayer spacings, providing platforms for the rational construction of heterostructures.

MXene-based composites and hybrids have been extensively investigated for a wide range of catalytic applications,[5,6] including photocatalytic (PC), electrocatalytic (EC), and photoelectrocatalytic (PEC) reactions such as the hydrogen evolution (HER),[7] oxygen evolution (OER), oxygen reduction (ORR),[8] carbon dioxide reduction (CO_2RR), nitrogen reduction (N_2RR) reactions and others, as summarized in Figure 1b. Among these research fields, HER and OER represent the most intensively explored topics, accounting for 28.7% and 10.4% of reported studies, respectively. Research on OER is particularly crucial for the advancement of clean energy technologies, including water splitting and metal-air batteries, in which the sluggish oxygen evolution process remains a major performance bottleneck.[9] Consequently, the development of cost-effective and high-performance OER catalysts is indispensable for enabling scalable hydrogen production and sustainable energy conversion systems. Achieving durable and

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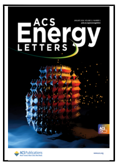

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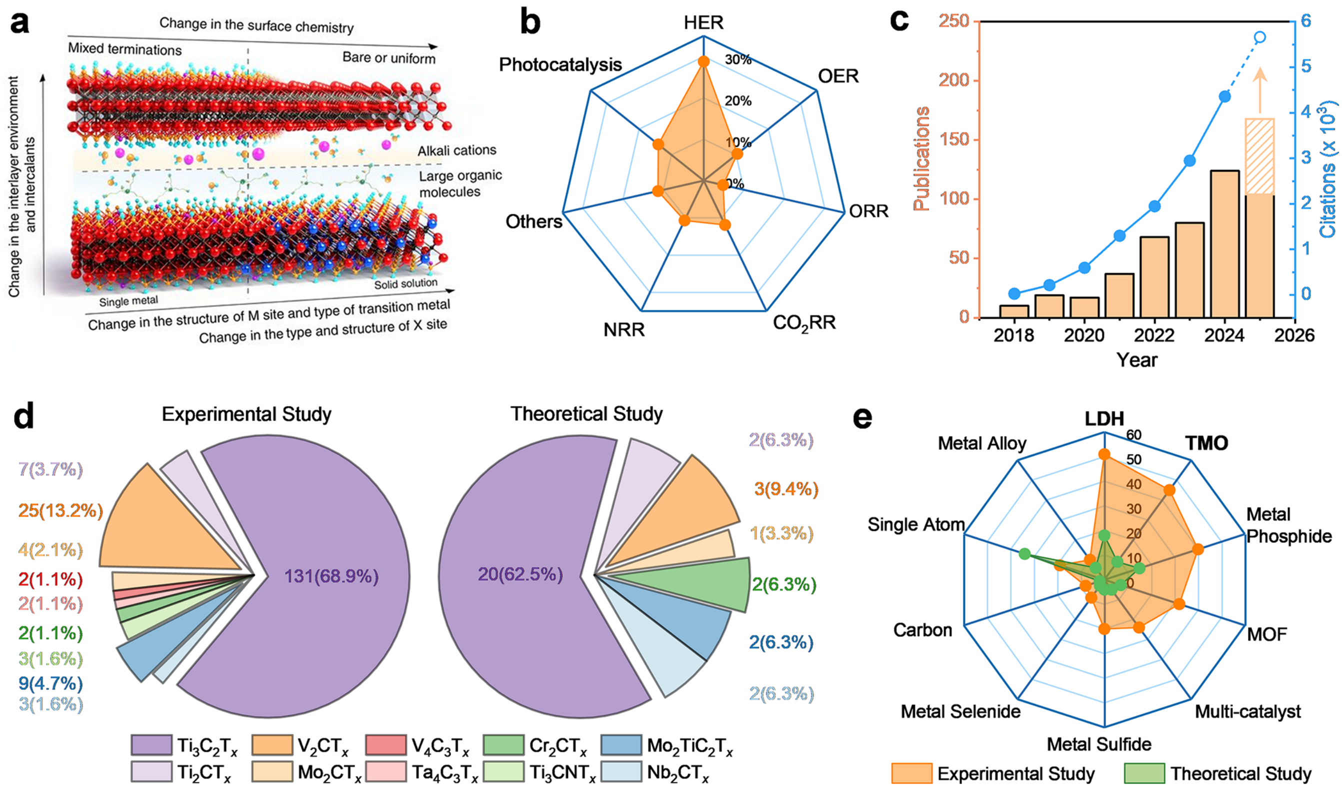

Figure 1. (a) Schematic illustration of different compositional and structural factors determining electronic and optical properties of MXenes.[10] Copyright 2021 American Association for the Advancement of Science. (b) Application of MXene in HER, OER, ORR, CO_2RR, NRR and other catalytic reactions including photochemical removal of pollutants. (c) Number of publications of MXene hybrids for OER and their increasing impact evidenced by citations. (d) Publications of MXene that have been investigated in experimental and theoretical studies for OER applications. (e) Up-to-date publications on MXene-based catalysts developed. Orange shape indicates experimental research while green data represents theoretical study. All data were obtained from Web of Science (September 2025) using general topic words, such as "MXene", "OER", and "LDH".

efficient OER electrocatalysts typically requires the construction of sophisticated heterostructures and the implementation of advanced design strategies.

It has been demonstrated that MXenes can serve both as precursors for active catalysts and as highly conductive support in OER systems. Remarkable progress has been achieved in this field, as reflected by the rapid growth in related publications—from fewer than 10 papers before 2018 to approximately 130 publications in 2024 and over 100 in 2025 (Figure 1c). However, early studies revealed that pristine MXenes possess negligible intrinsic activity toward oxygen catalysis, necessitating the incorporation of exogenous active species into the MXene matrix to construct high-performance MXene-based electrocatalyst composites.[11] Recent research on MXenes-based OER catalysts has therefore focused on developing hybrid systems, in which MXenes are integrated with secondary components that exhibit outstanding OER activity, including transition metal oxides (TMO), layered double hydroxides (LDHs), metal phosphides/nitrides/sulfides and nanometal alloys, to achieve synergistic effects and enhance catalytic performance.[12] Representative MXenes and their corresponding active phases employed in these hybrid systems are illustrated in Figure 1d,e. Notably, $Ti_3C_2T_x$ accounts for approximately 68% of experimental studies and 62.5% of theoretical investigations reported in the literature, underscoring its central role in MXene-based OER research (Figure 1d). The predominant development of $Ti_3C_2T_x$ can be largely attributed to its well-established synthesis protocols,[13] as well as exceptional electrical conductivity (up to 20,000 $S \cdot cm^{-1}$, the highest among known MXenes).[3] Owing to these advantages, $Ti_3C_2T_x$ is anticipated to retain its dominant role in development of MXene-based OER electrocatalysts in the foreseeable future.

An increasing number of new MXenes are being investigated in diverse MXene-based composites/hybrids with OER-active species both experimentally and theoretically, including V_2CT_x,[14,15] $TiNbCT_x$,[16] $Nb_4C_3T_x$,[17−20] and $Ta_4C_3T_x$.[21,22] For instance, the study on MOOH@$V_4C_3T_x$ (M = Ni, Fe, V) nanohybrid, featuring monolayer MOOH adsorbed on O-terminated $V_4C_3T_x$, revealed that $V_4C_3T_x$ enables the migration of metal atoms from the inner layers to the surface during reactive surface modification, which is not typically observed in M_2X and M_3X_2 MXenes.[23] This finding suggests that the presence of molecularly thin layers within MXene structure play a positive effect to lower the overpotential and improve the structural stability. Additionally, the introduction of metal elements and metal bonds potentially provides important opportunities to tailor catalytic active sites and modulate the distribution of electrons through interfacial engineering.[24−26] In particular, the development of MXenes with new composition is anticipated to redistribute surface charge and strengthen metal-substrate interactions (MSI) between catalytic active metal sites and MXene supports.[5,27−29] Such interfacial electronic modulation can effectively reconstruct the energy band structure, thereby facilitating the selective adsorption of oxygen-containing intermediates (e.g., *OOH and *OH species) and ultimately lowering the energy barrier of the rate-determining step (RDS) in the OER pathway.[30] This process also suggests a possible transition of the OER mechanism from the conventional adsorbate evolution mechanism (AEM) to the lattice oxygen mechanism (LOM) or the oxide path mechanism (OPM). The incorporation of (oxy)hydroxide species, in particular, can dynamically restructure the interfacial electronic landscape and stabilize key reaction intermediates, thereby offering a viable strategy to optimize catalytic performance.[31]

> Newly developed multimetal MXenes provide opportunities to tailor catalytic active sites by strengthening metal-substrate interactions.

In the context of OER-active materials incorporated into MXene-based electrocatalysts, TMOs and LDHs stand out as the most extensively employed secondary components, accounting for more than half of the publications (Figure 1e).[11,32−35] LDHs, in particular, offer a cost-effective alternative and compositionally tunable platform with high ion-exchange capacity and structural versatility, making them highly attractive for scalable applications in energy conversion and environmental remediation, especially under alkaline solutions.[34,35] However, the inherently low electrical conductivity of LDHs restricts efficient electron transport and limits access to active sites, thereby necessitating their integration of conductive species—such as MXenes—to enhance overall electrochemical performance.

Several comprehensive reviews have summarized recent advances in MXene-based electrocatalysis, with particular emphasis on synthesis strategies, composite catalyst design,[6,11,33,36,37] and mechanistic understanding supported by *in situ* characterization techniques.[32] It has been recognized that several indispensable factors of MXene critically influence the catalytic behavior of MXene-based systems, including their electrical conductivity, surface functional groups, metal-substrate interactions, and the utilization efficiency of active sites (Figure 2a).[32]

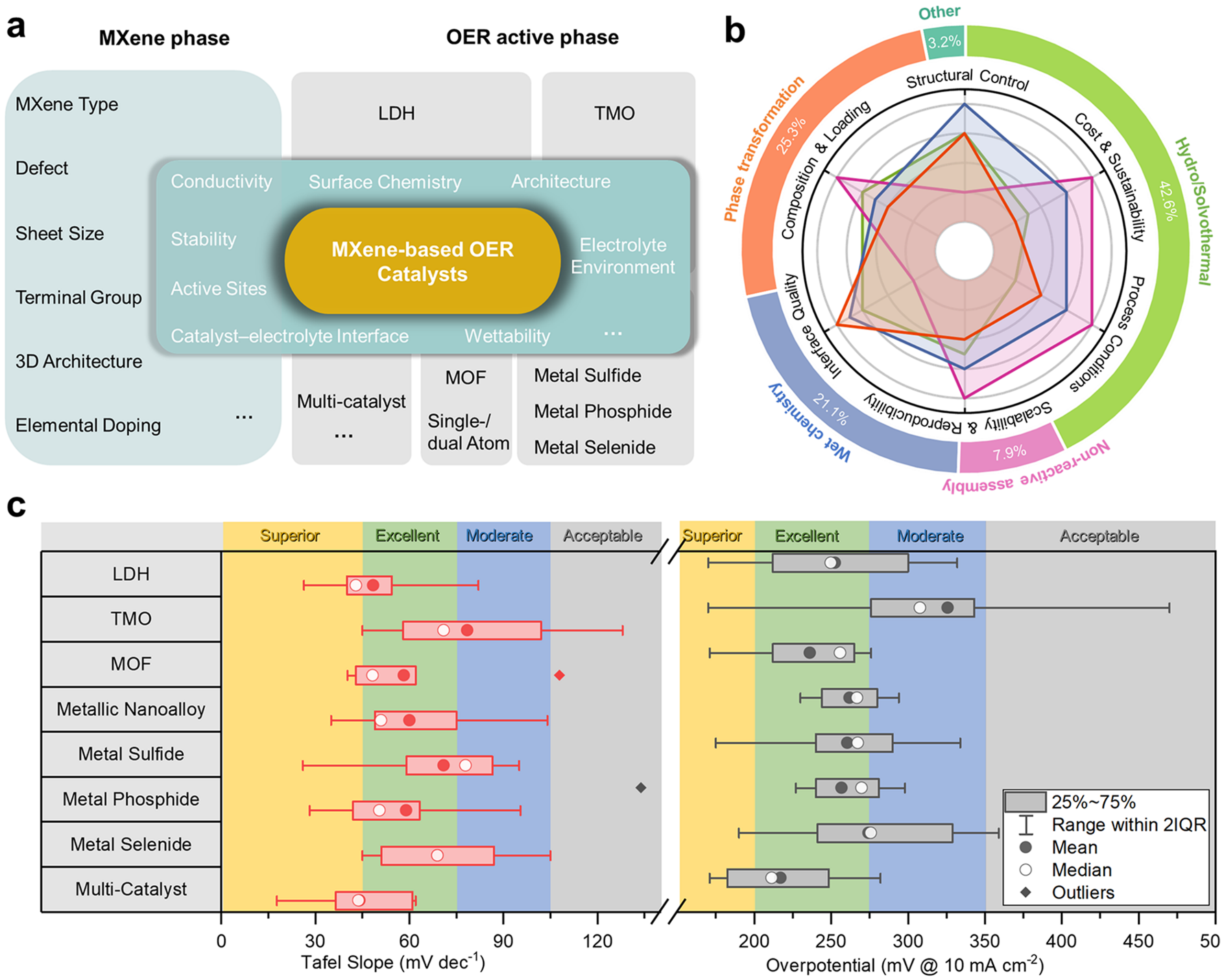

Figure 2. (a) Schematic diagram illustrating the key factors affecting MXene-based OER catalyst performance, and parameters to design MXene phase and active OER phase. (b) Radar map of six key evaluation factors (inside) and the up-to-date popularity of four synthesis strategies indicated by the percentage in literature (the outside doughnut plot). (c) Interquartile range (IQR) of OER overpotential at 10 mA cm^{-2} and Tafel slope for several commonly studied MXene-based composite/hybrid catalysts. The performance is grouped into four broad categories according to these values, without considering variations in measurement conditions or substrate effects.

> MXene sheets provide large-area substrate for loading OER catalysts, but the performance is highly dependent on the interfacial engineering and accessibility of active sites, which result in variability among different catalytic systems.

When designing MXene-based OER catalysts, the choice of synthesis method plays a critical role in determining catalytic performance. Currently, to integrate MXenes with various OER-active phases, a wide range of strategies has been explored, including hydro/solvothermal synthesis, nonreactive assembly (e.g., solution mixing, filtration, drop-casting and spray-coating), wet-chemical methods (e.g., ion adsorption, *in situ* growth, electrodeposition, cosedimentation), and phase transformation techniques (e.g., annealing, sulfidation, elemental doping).[33,38] A radar map summarizing these approaches across six key evaluation criteria is shown in Figure 2b. Among them, hydro/solvothermal synthesis is the most commonly employed method due to its strong structural controllability, but it is often constrained by poor scalability and harsh reaction conditions, particularly in the case of degradable MXenes.[39] Nonreactive assembly methods are used

> Precise control over the interfacial connection/bonding and 3D architecture morphology—especially in the growth of LDHs and TMOs—is essential for optimizing catalytic performance.

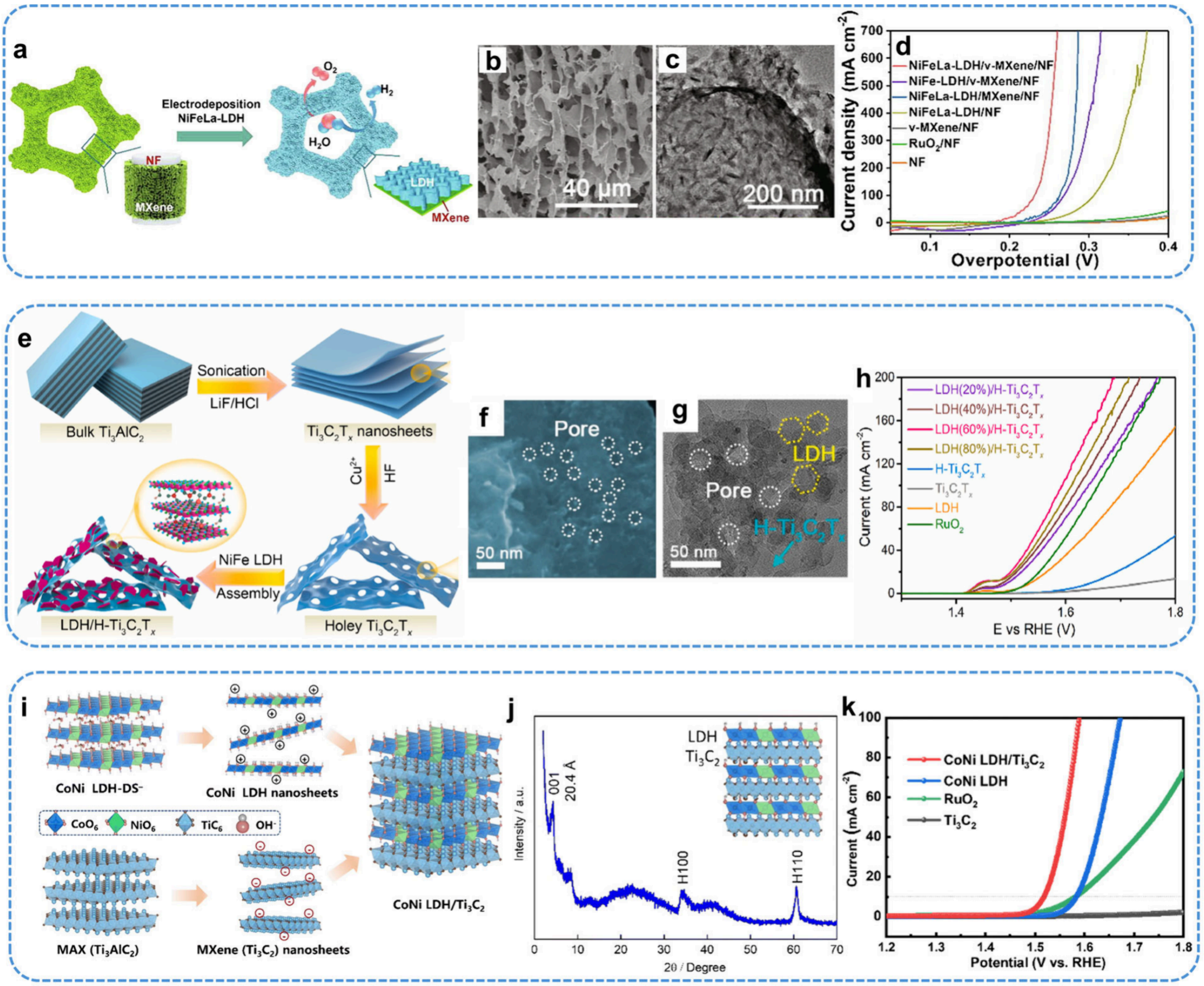

Figure 3. (a) Schematic illustration of the fabrication of NiFeLa-LDH/v-MXene/NF. Representative (b) scanning electron microscopy and (c) transmission electron microscopy images. (d) linear sweep voltammetry (LSV) curves. Reproduced with permission.[50] Copyright 2022, Elsevier. (e) Schematic illustration of the synthetic procedures of Ni−Fe LDH/H−$Ti_3C_2T_x$. (f) holey $Ti_3C_2T_x$ MXene nanosheets and (g) LDH/H−$Ti_3C_2T_x$ nanoarchitecture. (h) Representative LSV curves. Reproduced with permission.[24] Copyright 2023, Elsevier. (i) 2D assembly of LDH/MXene superlattice-like structures, (j) XRD pattern, (k) LSV curves. Reproduced with permission.[54] Copyright 2025, The Royal Society of Chemistry.

to fabricate MXene-based composites without inducing chemical reactions between the components, which are advantageous for their simplicity, low cost, and broad compatibility with various OER catalysts. Nevertheless, they typically lack precise control over interfacial bonding and structural integration, which can limit catalytic performance. Electrochemical deposition, as a representative wet-chemical method, offers a well-balanced combination of interfacial quality and controllability, making it highly suitable for precise and scalable catalyst fabrication. This comparison underscores the inherent trade-offs among different synthesis methods and highlights the emerging trend toward hybrid or optimized strategies to achieve comprehensive electrocatalytic performance. For instance, phase transformation strategies generally induced by heat treatment are often applied to modify catalysts initially synthesized via wet-chemical or hydro/solvothermal methods, enabling the controlled conversion of hydroxides into oxides, sulfides, or phosphides. Such postsynthetic modifications, which are generally challenging to achieve through alternative routes, allow for effective tuning of the electronic structure and surface properties, thereby enhancing catalytic activity.[22,30] Among all these approaches, ensuring firm anchoring or fixation of the active catalytic species onto the MXene surface is particularly critical for the preparation of stable and efficient composites.[40] Consequently, the selection of synthesis route is often governed by the type of active species combined with MXenes, underscoring the strong interdependence between synthesis strategy, structural design, and catalytic efficiency.[6,41]

A wide variety of exogenous active materials, including LDHs, TMOs, metal organic frameworks (MOFs), metallic nanoalloys, and chalcogenide- or phosphide-based compounds, have been rationally integrated with MXenes to achieve synergistic effects. Among these materials, LDHs and TMOs have attracted particular interest owing to their tunable metal composition, rich redox chemistry, excellent structural and morphological compatibility with MXene nanosheets. As illustrated by the performance statistics in Figure 2c, LDH- and TMO-based MXene composites exhibit particularly outstanding OER activities under alkaline conditions, surpassing most other material categories. Accordingly, the following sections summarize recent progress of LDH/MXene and TMO/MXene hybrids, emphasizing how interfacial engineering and morphology control modulate their electronic structures and catalytic properties.

LDHs constitute a class of layered materials composed of positively charged metal-hydroxide layers and charge-compensating interlayer anions.[35,42] Benefiting from the layered structure and anion-exchange capability, LDHs exhibit remarkable structural tunability. Their flexible lattice framework allows the incorporation of multiple transition metals such as Ni, Fe, Co, and Mn, which can synergistically modulate electronic structures and enhance catalytic activity. Specifically, multimetal incorporation generates synergistic active sites, while the intercalation of functional anions or molecules expands interlayer spacing, facilitating exfoliation into monolayer nanosheets. These nanosheets offer accelerated mass transport and enhanced catalytic kinetics.[35] Such features not only broaden the application of LDHs across various catalytic reactions but also render them highly promising for OER. However, their practical implementation is often constrained by limited electrical conductivity and strong aggregation tendencies. To address these limitations, LDHs are typically hybridized with conductive substrates to enhance charge transfer and catalytic efficiency.[42−44] Carbon-based substrates, particularly graphene, have been widely utilized due to their high surface area and excellent conductivity. When hybridized with these carbon supports, LDHs exhibit improved electrical conductivity and energy-storage capability, enabling their applications in electrochemical devices such as metal-air batteries.[45−47] Nevertheless, conventional carbon materials generally required chemical modification to graphene oxide (GO) or its reduced form (rGO) before integration, which inevitably compromises their conductivity and structural stability.[48,49] To overcome this issue, MXenes have recently emerged as superior alternatives to conventional carbon substrates.

Typically, the synthesis of LDH/MXene composites involves a two-step procedure. In this approach, MXene is first synthesized and subsequently employed as a substrate for the deposition of LDH nanostructures or ordered arrays. As depicted in Figure 3a, one representative example employed the electrodeposition of vertically aligned MXene (v-MXene) on nickel foam (NF) substrates, followed by the growth of hierarchical lanthanum-doped NiFe-LDH nanosheets, yielding the NiFeLa-LDH/v-MXene/NF system. The resulting architecture shown in Figure 3b,c facilitated rapid ion diffusion and electron transport, while maximizing the exposure of active sites. Consequently, the catalyst achieved markedly enhanced OER performance, attaining the commercially relevant current density of 500 mA cm^{-2} with excellent operational stability (Figure 3d).[50] Similarly, Yu *et al.*[51] proposed an alternative strategy by exploiting the negatively charged surface T_x groups of MXene to electrostatically assemble FeNi-LDH nanostructures into vertically oriented 3D arrays. Such vertical configuration effectively suppressed aggregation, while substantially enhancing the electrochemically active surface area and improving charge transfer kinetics. As a result, the FeNi-LDH/Ti_3C_2 hybrid demonstrated superior OER activity, faster reaction kinetics, and excellent durability compared to the physical mixture (FeNi-LDH + Ti_3C_2 MXene) and graphene-based counterpart in alkaline media.

Apart from the incorporation of directionally aligned channels within catalyst architectures, nanoscale porosity can also be deliberately engineered by introducing defects or holes on MXene sheets, thereby enhancing electrolyte transport and enabling high-current-density operation. Based on this concept, Huang *et al.*[24] fabricated $Ti_3C_2T_x$ with numerous nanosized in-plane holes (H−$Ti_3C_2T_x$) through controlled oxidation of $Ti_3C_2T_x$ nanosheets in $CuSO_4$ solution, followed by HF etching to remove the TiO_2 species. As illustrated in Figure 3e−g, the obtained H−$Ti_3C_2T_x$ served as a highly conductive scaffold for hydrothermal deposition of Ni−Fe LDH nanolayers. The optimized Ni−Fe LDH/H−$Ti_3C_2T_x$ hybrid catalyst delivered outstanding bifunctional electrocatalytic performance for both HER and OER, exhibiting low overpotentials, small Tafel slopes, and excellent long-term cycling stability (Figure 3h). These superior properties can be attributed to the synergistic structural merits of the composite: (i) the excellent electronic conductivity and abundant edge defects on the basal plane, which facilitated rapid charge transfer and provided abundant nucleation sites to physically and chemically anchor secondary components, effectively suppressing their aggregation; (ii) the hierarchical porous structure spanning macro, meso, and micropores, which enlarged the accessible surface area and enhanced mass transport during electrocatalysis.

In addition to direct growth of LDHs on MXenes, a distinctive superlattice-like structure can be constructed via face-to-face heteroassembly of monolayer LDH nanosheets with MXene layers. As illustrated in Figure 3i, this 2D assembly is achieved through electrostatic attraction between positively charged LDH nanosheets and negatively charged MXene nanosheets. Our previous work first demonstrated that oppositely charged nanosheets, such as oxides and LDHs, can be alternately stacked to form superlattice-like structure.[35,52,53] The heteroassembly of such superlattices enables electronic charge redistribution across adjacent layers, thereby promoting strong interlayer coupling. These interactions can induce lattice distortions or subtle structural rearrangements within the unilamellar nanosheets, which in turn modulate their physiochemical behavior. Consequently, synergistic effects between molecularly thin layers enhance both catalytic activity and structural stability. Furthermore, the electronic conductivity and catalytic performance of these superlattices can be tuned by judicious selection of constituent building blocks. For instance, CoNi-LDH/Ti_3C_2 superlattice composites were fabricated via the alternate stacking of LDH nanosheets and single-layer Ti_3C_2.[54] As revealed by X-ray diffraction (XRD) pattern in Figure 3j, the resulting superlattice structure confirmed periodic ordering of the two types of nanosheets. The intimate integration of LDH nanosheets and Ti_3C_2 facilitated charge transfer across the heterointerface, optimizing the distribution of electrons, and increasing the electron density of the interfacial active sites, thus enhancing the electron transfer efficiency inside the heterostructures. As a result, CoNi-LDH/Ti_3C_2 superlattice exhibited significantly reduced overpotential and smaller Tafel slope compared with its individual components (Figure 3k), confirming the effectiveness of molecular-scale LDH/MXene assembly for high-performance OER catalysis.

As summarized in Figure 2c, MXene/LDH catalysts exhibit an average overpotential of approximately 250 mV and a low Tafel slope of ~40 mV dec^{-1}, reflecting their excellent OER performance compared to other catalytic systems. Despite these promising results, several challenges persist. For example, LDHs are prone to phase transformation or partial dissolution during OER process, particularly under neutral and acidic conditions, which can alter the local environment of active sites and gradually degrade catalytic activity. In addition, the relatively weak interfacial bonding between LDH nanosheets and MXene layers may lead to delamination or peeling under gas evolution, as bubble-induced mechanical stress accumulates. Such interfacial instability increases the overall resistance and reduces the number of accessible active sites, ultimately compromising long-term electrocatalytic efficiency.[55]

A wide variety of TMOs, including perovskites,[56−58] spinels,[59] and amorphous oxides,[60,61] have long been recognized as promising electrocatalysts for OER owing to their earth abundance, facile preparation, and relatively high stability under alkaline conditions. Their catalytic behavior is strongly influenced by the flexible coordination environment and variable oxidation state of the transition-metal cations, which can be tuned through heteroatom doping or defect engineering. Incorporating multiple transition metals within a single oxide lattice often induces synergistic effects that enhance electronic conductivity and optimize active-site energetics, representing an effective strategy for boosting OER performance. Meanwhile, transition-metal hydroxides can also form *in situ* under OER operating conditions, providing large specific surface areas and compositional tunability for improved catalytic activity. Incorporating TMO nanostructures particularly nanoparticles with MXene sheets via solution mixing[40,62] and hydro/solvothermal methods[57,63,64] have demonstrated that TMO/MXene hybrids combine the structural flexibility and redox activity of oxides with the conductive networks of MXenes, resulting in enhanced catalytic efficiency and stability for OER.[65] Furthermore, strong interfacial interactions between TMOs and MXenes can optimize the adsorption/desorption energies of oxygen intermediates, thereby enhancing intrinsic catalytic activity.[62]

Importantly, TMOs serve as excellent bifunctional catalysts both for the OER and HER, making them highly attractive candidates for overall water splitting applications. For instance, a bifunctional Co-CoO/Ti_3C_2 composite was developed by constructing dual-active heterojunctions on a conductive MXene scaffold.[66] In this system, metallic Co sites promoted HER, while CoO domains provided OER activity. The Ti_3C_2 matrix showed enhanced conductivity and prevented catalyst aggregation. As a result, the composite exhibited excellent bifunctional electrocatalytic performance, demonstrating low overpotentials both for HER and OER. When applied in overall water splitting, the assembled electrolyzer required only 1.55 V to achieve a current density of 10 mA cm^{-2}, while maintaining remarkable durability, demonstrating the strong synergistic interaction between the Co-CoO heterostructure and the MXene support. Similarly, Lu *et al.*[57] reported a heterostructured perovskite oxide integrated with 2D $Ti_3C_2T_x$ MXene on nickel foam ($La_{1-x}Sr_xCoO_3/Ti_3C_2T_x$ MXene/NF). The hybrid system coupled solar-driven water evaporation with electrocatalytic water splitting, achieving enhanced OER activity with a low overpotential of 279 mV at 10 mA cm^{-2} and a small Tafel slope, outperforming conventional perovskite-based catalysts. The strong interfacial coupling between the perovskite oxide and MXene helped facilitate rapid charge transfer and optimize reaction kinetics, while interfacial evaporation could enrich local OH^- concentration and accelerate gas release, further boosting overall water-splitting performance.

However, in comparison with MXene/LDH catalysts, MXene/TMO hybrids exhibit a broader overpotential range (170−475 mV) with only moderate OER performance (Figure 2c). This wide distribution can be attributed to various factors such as morphology, crystallinity, defect density, surface area, and electronic structure of TMOs. In addition, structural inhomogeneity and insufficient interfacial contact between MXene and TMO components may impede electron transport and ion diffusion, further exacerbating performance inconsistencies. For instance, the urchin-like $RuCo_2O_4/Ti_3C_2T_x$@NF, featuring an increased active surface area, demonstrated remarkable OER activity, achieving a low overpotential of 170 mV at 10 mA cm^{-2}.[67] In contrast, Co_3O_4 quantum dots assembled on MXene nanosheets via van der Waals interactions showed a much higher overpotential of 340 mV at 10 mA cm^{-2}, mainly due to their limited electrical connectivity.[68] In another case, a layer-by-layer assembled $CoNiFe_2O_4$/MXene-based 2D/NPs/2D network exhibited improved mass transport attributed to its highly porous nature and enhanced surface exposure, which collectively improved electron transfer during the reaction.[69] These findings underscore the critical need for improved synthesis strategies and rational structural design to fully realize the electrocatalytic potential of MXene/TMO hybrids.

■ OUTLOOK

MXenes represent a rapidly expanding family of 2D materials with significant potential for OER catalysis, but their mechanistic roles and full capabilities in guiding the design of superior catalysts remain incompletely understood. A systematic evaluation of parameters such as MXene composition, surface terminations, hybridization strategies, structural design, and interfacial properties is crucial for the rational design of high-performance MXene-based catalysts.

Recent efforts have focused on low-temperature, solvent-free synthesis approaches to reduce cost and environmental impact, thus guiding the development of next-generation catalysts. As emphasized in this perspective, the choice of synthesis methods must be carefully aligned with the selected active species and MXene type to maximize OER activity. While Ti-based MXenes (e.g., $Ti_3C_2T_x$) have been extensively investigated, emerging multimetal MXenes, such as Nb−Ti, V−Ti and Mo−Ti systems, offer additional opportunities by introducing synergistic effects that modulate charge distribution and generate heterogeneous active sites. Moreover, selective surface termination engineering and defect modulation are essential strategies for tailoring the hydrophilicity, electronic structure and interfacial electron transfer to optimize catalytic performance. A deeper understanding of how these surface modifications impact electronic and catalytic properties will be critical for the rational design of high-performance MXene-based OER systems.

Interfacial engineering offers a powerful approach to boost catalytic performance by modulating electronic structure, accelerating charge transfer, and increasing the exposure of active sites. Precise control over interface engineering and morphology—especially in the hybridization of LDHs and TMOs—is essential for optimizing catalytic performance. MXene sheets serve as highly conductive scaffolds that enable the integration of active sites into 3D architectures, thereby improving the accessibility of OER reactants. However, as the distance between active sites and the conductive MXene sheet increases, the benefits to electrical conductivity diminish, limiting activity enhancement. Meanwhile, aggregation and restacking of MXene-based hybrids may introduce anisotropic charge-transfer pathways, particularly when there is a size mismatch between MXene sheets and active components. To overcome these issues, molecular-level face-to-face heteroassembly is advantageous for optimizing interfacial contact between MXene and the active species. An integrated approach that combines the nonreactive assembly techniques with surface functionalization, nanoscale structure design, and mild postsynthetic treatments is expected to enhance interfacial connectivity and structural coherence, while preserving the scalability and reproducibility essential for practical catalyst design. Consequently, achieving an optimal balance between interfacial connection/bonding and 3D architecture remains a key challenge for maximizing the number of accessible active sites on MXene surface.

High-current-density OER requires efficient delivery of reactants and rapid removal of products, as poor mass transport can cause bubble accumulation, increased resistance, and degraded catalytic performance. MXene nanosheets offer conductive frameworks that facilitate both electron and mass transport, thereby enhancing OER activity. Nevertheless, achieving stable operation at high current densities remains challenging due to the need for durable catalysts, efficient mass transport, and mechanically robust electrode architectures. In particular, the dynamics at the gas−liquid interface during bubble formation and accumulation warrant deeper investigation. Key factors such as catalyst adhesion, structural integrity, and resistance to delamination under dynamic operating conditions must also be addressed to pave the way for practical, industry-scale applications. In addition, the prevalent use of multilayer MXenes has not been accompanied by quantitative assessment of their accessible surface area, limiting understanding of how morphology features influence performance. Systematic studies on layer thickness, interlayer spacing, and structural configuration are therefore needed to optimize MXene-based hybrid catalysts for high-current-density applications.

Despite their promising activity, the long-term stability of MXene-based catalysts under oxidative conditions remains a significant challenge. Future research should focus on the development of oxidation-resistant MXene chemistries, the application of protective coatings, and the implementation of dynamic interface engineering to mitigate structural degradation. In addition, accelerated durability tests combined with detailed post-mortem analyses are essential to elucidate degradation mechanisms and guide the rational design of robust architectures suitable for industrial-scale water electrolysis.

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Notes

The authors declare no competing financial interest.

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