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REVIEW

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Understanding and resolving the heterogeneous degradation of anion exchange membrane water electrolysis for large-scale hydrogen production

Jia Lei^{1†}, Ziyi Wang^{1†}, Yunze Zhang¹, Min Ju¹, Hao Fei¹, Siyuan Wang¹, Chengxi Fu¹, Xinchang Yuan¹, Qiang Fu², Muhammad Usman Farid^{1,3}, Hui Kong⁴, Alicia Kyoungjin An^{1,3}, Runxu Deng⁵, Feng Liu⁵ and Jian Wang^{1,6*} 

Abstract

Anion exchange membrane water electrolysis (AEMWE) has seen rapid advancements over the past decade due to its promising role in green hydrogen production. Ensuring long-term functionality is as crucial as optimizing performance to achieve commercial viability and industrial integration. However, few studies have systematically discussed the degradation issues of this technology. Therefore, a thorough understanding of AEMWE degradation is needed to guide the design, assembly, operation, and maintenance of the device over its lifetime. To address this gap, this review systematically overviewed the heterogeneous degradation of AEMWE across different material and interface levels, focusing on several key components including catalysts, ionomers, membranes, and gas diffusion layers. The influences of these components and their interfaces on the catalytic efficiency, active site density, and mass and electron transfer capabilities were discussed. Moreover, the impacts of operation conditions, including temperature, electrolyte composition, and clamping pressure, on the stable operation of AEMWE were assessed. Accordingly, current mitigation strategies to resolve these degradation phenomena were rigorously evaluated. By offering insights into optimizing operations, designing materials, and improving assessment protocols for AEMWE, this work will contribute to enhancing its stability for large-scale hydrogen production.

Keywords Water electrolysis, Anion exchange membrane, Degradation mechanism, Hydrogen

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1 Introduction

With over 130 countries and regions committing to carbon neutrality targets, the world is accelerating its shift towards low-carbon economies to meet sustainable development goals. Hydrogen energy stands out as a promising solution amid global efforts to transition away from traditional fossil fuels and address climate change due to its cleanliness and environmental friendliness [1].

Anion Exchange Membrane Water Electrolysis (AEMWE) emerges as a promising technology in the field of hydrogen production, offering several distinct advantages over conventional alkaline water electrolysis (AWE) and proton exchange membrane water electrolysis (PEMWE) routes (Table 1). The primary structure of an AEMWE cell consists of an anion exchange membrane (AEM) and two catalytic electrodes. Typically, AEMWE employs dilute alkaline or pure water solutions as electrolytes, along with inexpensive non-precious metal catalysts and carbon-based membranes [2]. During operation, water undergoes electrolysis, splitting into hydrogen and oxygen gases. This process involves the oxygen

evolution reaction (OER) occurring at the anode and the hydrogen evolution reaction (HER) at the cathode, as shown in Fig. 1.

While AWE has achieved widespread commercialization and PEMWE has shown promise for dynamic response and compatibility with fluctuating renewable energy sources, AEMWE stands out by combining the low-cost attribute of AWE with the simplicity and efficiency of PEMWE. Currently, the anode and cathode catalysts used in commercial AWE are Raney Ni, costing approximately \$50/m². In contrast, PEMWE requires a significant investment in catalyst materials, approximately \$3,840/m², due to the use of precious metals like IrO₂ for the anode and Pt/C for the cathode, which enhance stability in acidic environments. The catalysts of AEMWE are much cheaper as they do not require expensive precious metals. For example, Co₃O₄ anode and CoFe₂O₄ cathode catalysts cost about \$500/m². Estimates indicate that when the stack scale reaches 1 MW, AEMWE's capital investment and levelized cost of hydrogen are approximately \$542 and \$3.69, respectively.

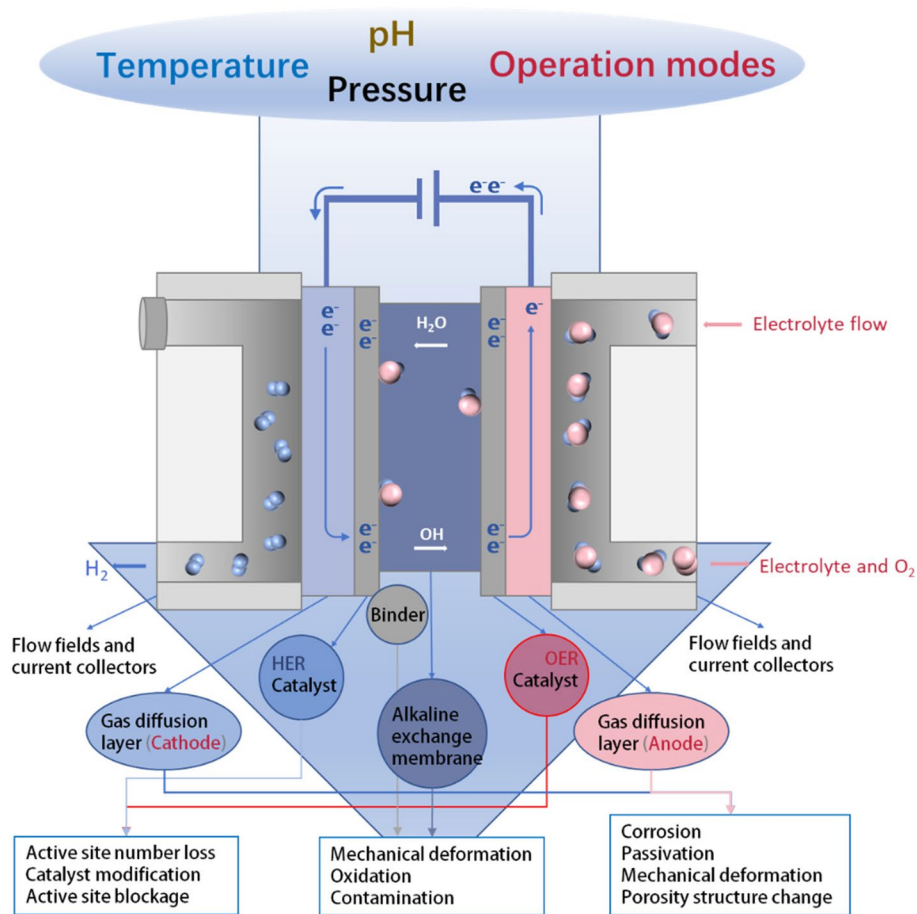


Fig. 1 Structure and degradation mechanisms of core components AEMWE

Table 1 Materials, components, operation conditions, and performance of alkaline water electrolyzer, PEMWE, and AEMWE

Specification	AWE	PEMWE	AEMWE
Component material			
Typical anode catalyst	Ni/Co/Fe-based	IrO ₂ /RuO ₂	Platinum-group metals-free transition metal oxides
Typical cathode catalyst	Ni/C-Pt	Pt/C	Ni/Co-based
Typical ionomer binder	No binder	Nafion	Anion exchange ionomer
Membrane	Asbestos/PBS	Nafion	AEM
Electrolyte	25–40 wt% KOH /NaOH	Water	KOH/Water /K ₂ CO ₃
Anode GDL	Ti/Ni/zirconium	Ti	Ni/Stainless steel
Cathode GDL	Stainless steel mesh	Carbon paper	Carbon paper
Supporting/separating component	Stainless steel	Ti, Au/Pt coated Ti	Stainless steel
Operation parameters			
Temperature	60–90 °C	50–80 °C	60–80 °C
Pressure	<3.2 MPa	3–4 MPa	<3 MPa
Performance			
Cell voltage	1.8–2.40 V	1.75–2.20 V	0.8–2.5 V
Current density	0.2–0.4 A/cm ²	0.6–10.0 A/cm ²	
Lifetime stack	<90,000 h	<20,000 h	>12,000 h
Degradation rate	<3 μV/h	<14 μV/h	
Device Lifetime	20–30 y	10–20 y	
Cost and benefit			
Anode catalyst loading (g/m ²)	50	20	20
Anode catalyst price (\$/m ²)	25 (Raney Ni)	~2940(99.9%IrO ₂)	~100 (Co ₃ O ₄)
Cathode catalyst loading (g/m ²)	50	5	20
Cathode catalyst price (\$/m ²)	25 (Raney Ni)	900 (50% Pt/C)	400 (CoFe ₂ O ₄)
Membrane price	~200	~300	~250
Capital Costs (\$/kW) (for 1 MW system)	796	587	(542)
Levelized cost of hydrogen (\$/kg H ₂)	4.15	4.16	(3.69)
Energy Efficiency (%)	60%	80%	
Hydrogen Purity	>99.5%	>99.999%	>99.99%

Additionally, the energy conversion efficiency and hydrogen purity of AEMWE are comparable to those of PEMWE, as shown in Table 1. [3, 4]

To date, most reported stability tests have lasted from a few hundred hours to a few thousand hours or have involved a few thousand start–stop voltage cycles [5–10]. The longest reported AEMWE operation has achieved 1 A/cm² stable operation for over 12,000 h (more than 1 year) with a minimal degradation rate of 1 μV/h, using NiFe₂O₄, Raney nickel, and X37-50 Dioxide membrane as the anode catalyst, cathode catalyst, and membrane, respectively. In addition, the dynamic cycling test also showed a low degradation rate of only 0.15μV/h over 11,000 cycles [11]. However, these metrics still fall short compared to the lifetime of the current AWE (60,000–90,000 h) and PEMWE (20,000–60000 h with negligible decay) [12, 13], and are insufficient to meet the 100,000-hour lifetime goal set by the International Renewable Energy Agency for 2050 [14]. Therefore, there is still

significant room for improving AEMWE to enhance its market competitiveness.

Several challenges related to stability must be addressed to realize the full potential of AEMWE technology. Firstly, the primary difficulty in advancing AEMWE technology lies in achieving both high catalytic activity and stability simultaneously. There is often a trade-off between catalytic activity and stability: catalysts with high activity tend to be unstable, while those with good stability generally exhibit lower activity [15]. Additionally, both catalyst properties and electrolysis conditions significantly influence AEMWE performance [16, 17]. This complexity makes it challenging to design advanced electrocatalysts that are both highly efficient and stable, posing a significant hurdle in the development of this promising technology. Secondly, the complex environment of an AEMWE, comprising multiple integrated components such as the catalyst layer, membrane, gas diffusion layers (GDLs), current collectors, and bipolar

plates, presents significant challenges in improving performance and stability. Core processes like electrochemical reactions, coupled mass and charge transport, and heat transfer all occur within this intricate system. The interplay of these processes complicates the identification of the dominant factors affecting performance and stability. Moreover, degradation can arise from multiple interacting factors, complicating the understanding of degradation phenomena and mechanisms and making it difficult to understand the underlying degradation phenomena and mechanisms of AEMWE [18]. Therefore, elucidating the failure mechanisms of AEMWE devices is crucial for improving their stability and promoting commercialization.

The failure of AEMWE has increasingly attracted significant attention. However, there are few systematic reviews that comprehensively overview the current understanding and mitigation strategies for AEMWE degradation. Previous reviews on water electrolysis have typically focused on individual components, such as catalysts [19], membranes [20], operating conditions [21], electrolyte impurities [22], and bubble management [23], without considering the complex interplay among these components and their interfaces. For instance, interactions between catalysts and binders, membranes, or electrolytes during electrolyzer operation can alter the physicochemical properties of these components, leading to issues such as catalyst dissolution, membrane breakage, and electrolyte contamination, which may degrade the performance of electrolyzer. A systematic analysis of the most recent progress in understanding and addressing the heterogeneous degradation of AEMWE devices is crucial for guiding their rational design and optimization for practical applications.

In this review, we explored the intricate mechanisms of degradation phenomena affecting AEMWE devices, from the material level—including catalysts, binders, AEM, and GDLs—to the interfaces of different components, investigating stabilization mechanisms for device performance. By elucidating these degradation pathways, we aim to provide valuable insights that can promote the development of strategies for enhancing the stability and efficiency of AEMWE technologies, thereby advancing their role in the transition toward a cleaner and more sustainable energy future.

2 Degradation of catalyst materials

One notable advantage of AEMWE is the use of non-precious metals (such as Ni, Fe, Co, and Mo) as electrode electrocatalyst materials [24]. Catalyst materials are crucial for facilitating the desired electrochemical reactions. However, these materials can undergo degradation due to various factors, including pH, operating temperature, electrolyte composition, and the intrinsic stability of the catalyst [19, 25]. The primary deactivation modes can be categorized into two main types: the loss of active sites and the loss of intrinsic catalyst activity. These modes include processes such as dissolution, depletion, segregation (where catalyst components separate or concentrate in specific regions or phases within the catalytic system), reconstruction, aggregation (where catalyst particles cluster to form larger aggregates), and active site blockage, as shown in Fig. 2 [26–28]. These degradation paths can be influenced by multiple factors and often interact with each other, leading to various degradation phenomena during AEMWE operation.

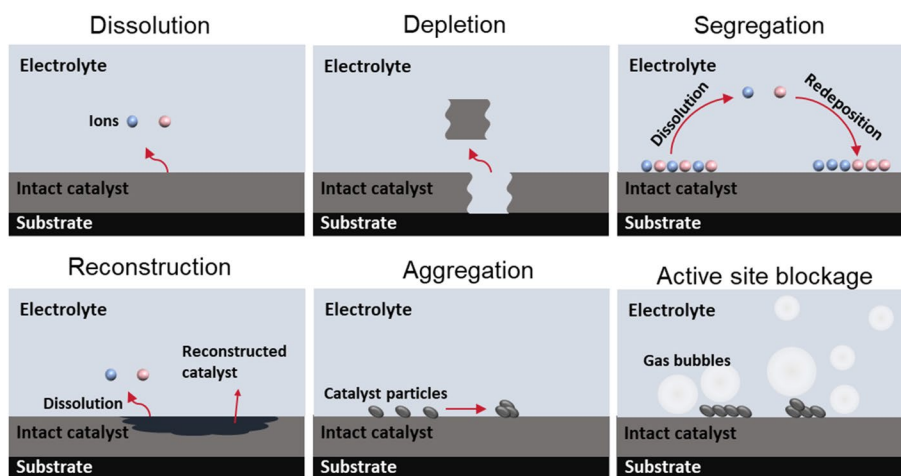


Fig. 2 The schematic diagrams of catalyst failure mechanisms: dissolution, depletion, segregation, reconstruction, aggregation, and active site blockage

2.1 Loss of active sites

A primary factor leading to catalyst degradation is the reduction in the number of active sites on the catalyst surface. Chemical degradation, characterized by the gradual loss of catalytic activity due to various chemical processes occurring at the surface of the catalyst—such as those induced by the alkaline environment, high temperatures, or the presence of reactive species like hydroxide ions—can result in the dissolution or leaching of active sites, thereby reducing catalytic activity over time.

2.1.1 Dissolution of active sites

Dissolution or corrosion, which compromises the structural integrity of catalyst materials and leads to the loss of active sites, is a common chemical degradation pathway for non-precious metal catalysts. The Pourbaix diagrams, which illustrate the stability of elements as a function of pH and electrode potential for four common transition metal catalysts—Co, Cu, Fe, and Ni—in aqueous electrolytes at ambient pressure and 25 °C, are shown in Fig. 3a. In these diagrams, shaded areas represent conditions under which the elements are susceptible to corrosion. Compared to Co, Ni, and Mo, Fe is thermodynamically unstable in high-pH environments and tends to leach from the electrode in alkaline solutions, even without the application of an external potential [29, 30]. The high dissolution rate of Fe leads to a decrease in OER activity during the initial cycles, thus compromising its effectiveness as an OER catalyst. Therefore, for catalyst materials containing iron, it is crucial to consider the impact of iron dissolution on catalyst performance.

Introducing a trace amount of Fe into the electrolyte has been proposed as a strategy to counteract the effects of Fe dissolution, resulting in a significant enhancement in the stability of Fe-based catalysts. As depicted in Fig. 3b1, in the Fe-free electrolyte, the Fe content in the electrode rapidly decreased within the first 10 min. Concurrently, the OER activity also rapidly declined, which was attributed to the dissolution of Fe ions from the electrode and the subsequent reduction in the number of active sites. When a trace amount of Fe was added to the electrolyte, as shown by the results from isotopic labeling and inductively coupled plasma mass spectrometry

(ICP-MS) in Fig. 3b2, the original Fe content in the catalyst on the electrode still decreased, but Fe ions in the electrolyte were deposited on the surface of the catalyst to compensate for this loss. The dissolved Fe helped to maintain the stability of the Fe content on the electrode. Chronoamperometry (CA) tests, illustrated in Fig. 3b3, also demonstrated that the addition of a trace amount of Fe to the electrolyte effectively preserved OER activity [31].

The implementation of protective layers on catalyst surfaces has emerged as a robust strategy to prevent direct electrolyte contact and mitigate catalyst dissolution. Various materials, including carbon coatings, conductive polymers, and stable oxides, are frequently employed as protective barriers. A notable advancement in this field was achieved by Keisuke Obata, who developed a highly durable NiFeO_x OER electrocatalyst by anodically depositing a CeO_x layer. This CeO_x layer, composed of mixed oxides and hydroxides, effectively obstructed the diffusion of redox ions while allowing the permeation of OH⁻ and evolved O₂. The enhanced stability of the OER catalyst was attributed to the permselectivity of the CeO_x layer, which regulated the diffusion of redox ions such as iodide, ferrocyanide, and dissolved metal ions between the electrolyte and the OER catalysts (Fig. 3c1). As shown in Fig. 3c2, the characteristic redox peaks at around 1.33 V vs. reversible hydrogen electrode (RHE) for ferrocyanide ions disappeared, while those at around 1.42 V vs. RHE for Ni ions remained unchanged after the CeO_x coating. Moreover, introducing specific ions or molecules into the electrolyte could further enhance the stability of the catalysts by forming protective complexes on their surfaces, thereby reducing dissolution. By incorporating these protective strategies, substantial improvements in the durability and performance of OER catalysts can be achieved [32].

Similarly, metal dissolution has also been identified as a major factor degrading the HER process. In Ni₄Mo nanoparticle alloy catalysts prepared by electrodeposition, Mo is considered the primary HER catalytic active site. However, during the HER process, Mo continuously dissolves in the form of MoO₄²⁻, leading to a reduction in the number of active sites and inhibiting the HER process.

(See figure on next page.)

Fig. 3 **a** Pourbaix diagrams of Co (a1), Cu (a2), Fe (a3), and Ni (a4) in aqueous electrolytes at ambient pressure and 25 °C. The insets show the voltage–pH ranges that the anode and cathode catalysts may experience in an AEMWE [30]. Reproduced under the terms of the IEA. CC BY 4.0 license. Copyright 2022, National Research Council of Canada. **b** the total amount of Fe in the Fe-NiO_xH_y electrode obtained by in situ ICP-MS method (b1, b2) and corresponding OER activity (b3) during CA in 1 M KOH electrolyte containing 0.1 ppm Fe [31]. Copyright 2020, The Author(s), under exclusive license to Springer Nature Limited. **c** the schematic diagram of the mechanism of the enhanced stability of the NiFeO_x OER electrocatalyst achieved through increased selectivity via the introduction of a CeO₂ coating (c1) and the CV curves of the NiFeO_x and CeO₂ coated NiFeO_x electrodes in 1 M KOH electrolyte with and without the addition of K₄Fe(CN)₆ solution to prove the permselectivity of the coating layer (c2) [32]. Copyright 2018, John Wiley and Sons

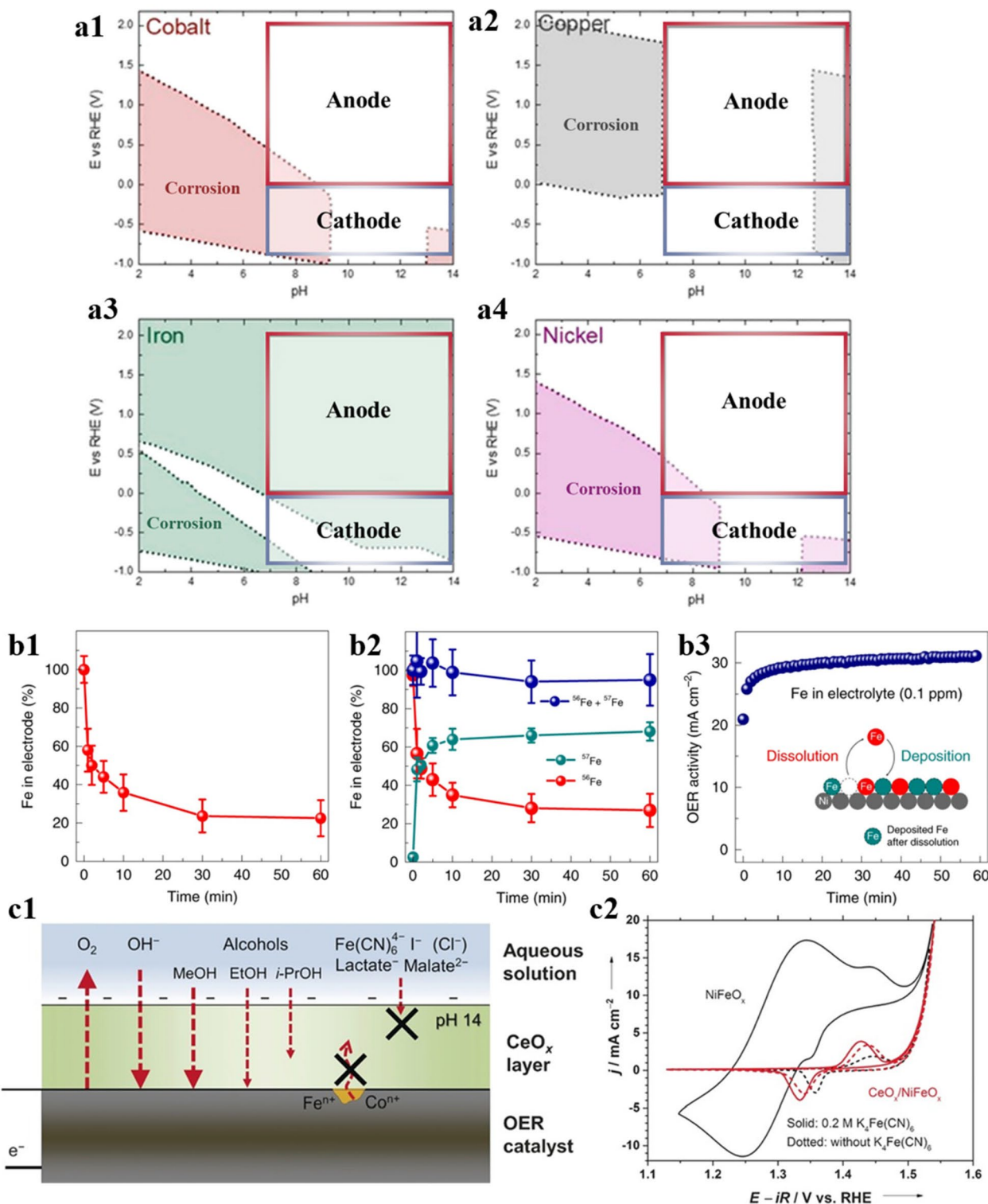


Fig. 3 (See legend on previous page.)

When a layer of NiMoO_4 was electrodeposited onto the surface of Ni_4Mo to form a $\text{Ni}_4\text{Mo}/\text{NiMoO}_4$ heterostructure, the MoO_4^{2-} in NiMoO_4 and the MoO_4^{2-} dissolved

in the solution from Ni_4Mo synergistically promoted the formation of $\text{Mo}_2\text{O}_7^{2-}$. This species, containing high-valence Mo^{6+} , facilitated the formation of Mo-H

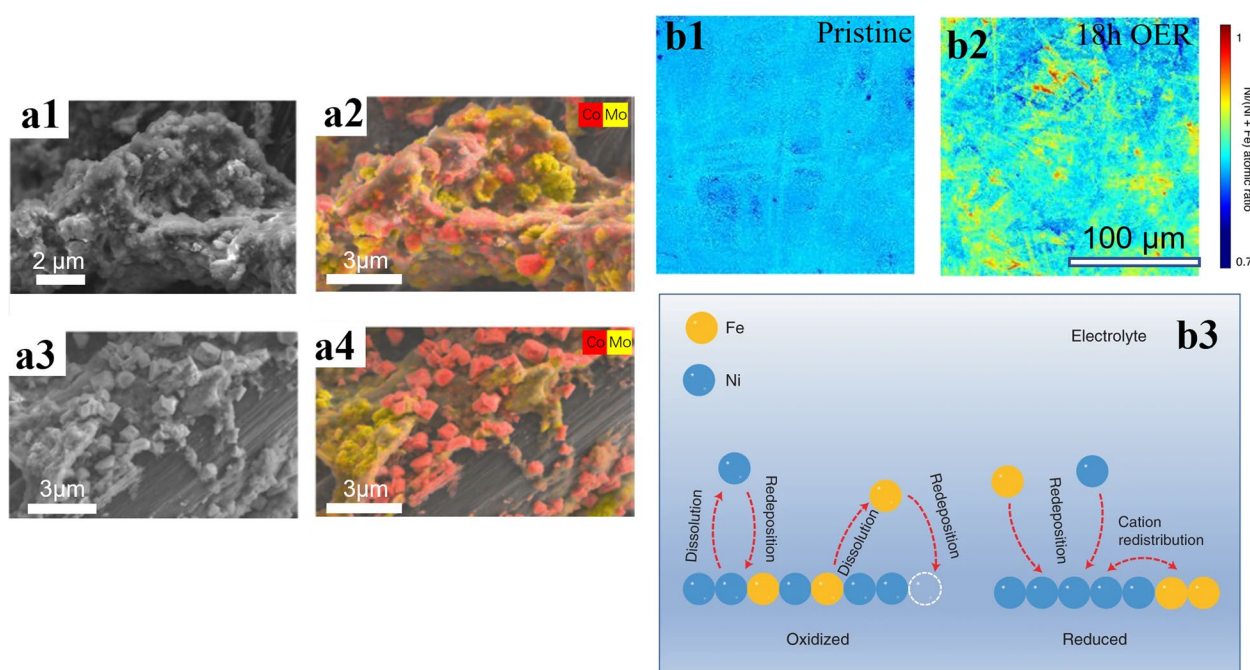


Fig. 4 **a** The SEM and EDS of $\text{Co}_{0.5}\text{Mo}_{0.5}\text{S}_x$ cathode catalyst before (a1 and a2) and after electrolysis (a3 and a4) [34]. Copyright 2022, American Chemical Society. **b** Ni/(Ni+Fe) atomic ratio distribution of mixed Ni-Fe hydroxide before (b1) and after 18 h of CA measurement at 1.6 V versus RHE (b2). These figures were generated by a pixel-by-pixel analysis of synchrotron X-ray fluorescence microscopy images of Ni and Fe. (b3) The schematic diagram of the compensatory effect mechanism of adding Fe ions in the electrolyte during CV [35]. Copyright 2020, The Author(s), under exclusive license to Springer Nature Limited

intermediates. The generated $\text{Mo}_2\text{O}_7^{2-}$ was adsorbed on the electrode surface, thereby enhancing the HER process [33].

2.1.2 Segregation of active sites

The segregation of active sites in water electrocatalysts during operation is a critical factor contributing to their instability, severely affecting the efficiency and longevity of electrocatalysts used in water splitting. Results from X-ray photoelectron spectroscopy (XPS) and energy dispersive X-ray spectroscopy (EDS) have indicated that the irreversible current degradation observed in an AEMWE cell employing $\text{Co}_{0.5}\text{Mo}_{0.5}\text{S}_x$ as the cathode catalyst and Ir black as the anode catalyst may be attributed to the spatial segregation of Co and Mo. In this setup, Co catalyzes the OER, while Mo facilitates proton transfer. The segregation of these elements, as illustrated in scanning electron microscope (SEM) and EDS images before and after electrolysis (Fig. 4a2 and a4), disrupts this synergistic interaction, leading to a decline in catalytic activity [34]. This segregation phenomenon is particularly significant for NiFe-based catalysts, where Fe is thermodynamically prone to dissolve into the electrolyte, while Ni exhibits greater stability. As shown in Fig. 4b, the distribution of Ni/(Fe + Ni) atoms in mixed Ni-Fe hydroxide electrocatalysts became broader after CA tests due to extensive Fe

dissolution. Operando extended X-ray absorption fine structure measurements showed that the lattice distortion in Ni-Fe hydroxides was more significant than that in $\text{Ni}(\text{OH})_2$ due to discrepancies in the local structures around Fe and Ni centers upon oxidation during OER, which caused Fe expulsion from the lattice to relieve this distortion. The dissolved Fe then redeposited at the edge sites of the NiOOH lattice and formed a FeOOH secondary phase. This process created an interface between the FeOOH phase and the host NiOOH lattice. Over time, the continuous growth of this FeOOH-NiOOH interfacial region led to the complete partitioning and segregation of the FeOOH phase from the mixed hydroxide catalyst. This structural evolution at the catalyst/electrolyte interface destabilized the mixed hydroxide structure, ultimately leading to deactivation and degradation of the overall catalytic performance [35].

Interestingly, compared to the chronoamperometry (CA) process, the segregation of Fe was less pronounced during the cyclic voltammetry (CV) process. Density functional theory (DFT) calculations suggested that the reduction potential could facilitate the redeposition of Fe ions onto the catalyst surface, as shown in Fig. 4b3. This reversible phase segregation implies that cathodic polarization during CV helps to mitigate segregation phenomena. Stability tests also revealed that incorporating

intermittent reduction steps during continuous CA testing significantly enhances catalyst stability compared to continuous CA alone [35]. Additionally, reducing the particle size of the catalyst and increasing the specific surface area can expose more active sites, allowing for a more uniform OER process on the catalyst surface. This approach may reduce lattice distortion caused by uneven reactions, enabling the catalyst to better withstand structural changes during OER. It has been proposed as a potentially effective method to suppress phase separation, although its impact on long-term stability remains to be further investigated [35, 36].

2.1.3 Particle agglomeration

Particle agglomeration significantly compromises the efficiency of water electrolysis. When catalyst particles agglomerate, they form larger clusters with a reduced surface area relative to their volume. This reduction in surface area results in fewer active sites available for the electrochemical reactions crucial for water splitting. During the operation of AEMWE, high current densities and potentials, coupled with substantial gas bubble generation and variations in ion concentration and pH gradients within the electrolyte, can lead to the migration and agglomeration of catalyst particles. This effect is exacerbated if the binding strength between the catalyst particles and the electrode substrate is weak and cannot resist the erosion caused by bubbles and flowing electrolyte [21]. For example, agglomeration of Pt particles in

commercial Pt/C catalysts has been observed using identical location transmission electron microscopy (TEM). As shown in Fig. 5a, agglomeration was detected after 168 h of CA testing (Fig. 5a2), with a slight increase in the average particle size (Fig. 5a4). This phenomenon is likely due to the hydrogen gas generated at the Pt/C interface, which reduces the interaction between Pt and the carbon support, promoting the migration of Pt particles and leading to the formation of Pt agglomerates and a reduction in the HER active sites [37].

Increasing the adhesion between the catalyst and the supporting substrate to inhibit catalyst migration during the reaction could effectively mitigate the agglomeration problem. For instance, SnO₂ coating can protect Pt particles from agglomeration and the carbon support from corrosion. Figure 5b shows the TEM images of Pt particles on the carbon nanofiber substrate with (Fig. 5b2) and without (Fig. 5b1) the deposition of SiO₂ after 10,000 CV cycles. The deposition of SiO₂ on the carbon nanofiber substrate significantly reduces Pt particle agglomeration, and the Pt particle size distribution is broader with SiO₂ [38]. Another study investigated the effects of various nano-SiO₂ coating thicknesses on Pt agglomeration in Pt/C catalysts. TEM and linear sweep voltammetry (LSV) results before and after accelerated durability tests showed that Pt/C particles coated with SiO₂ exhibited improved stability compared to pure Pt/C particles. Additionally, stability improved with increased coating thickness. However, excessively thick coatings may block

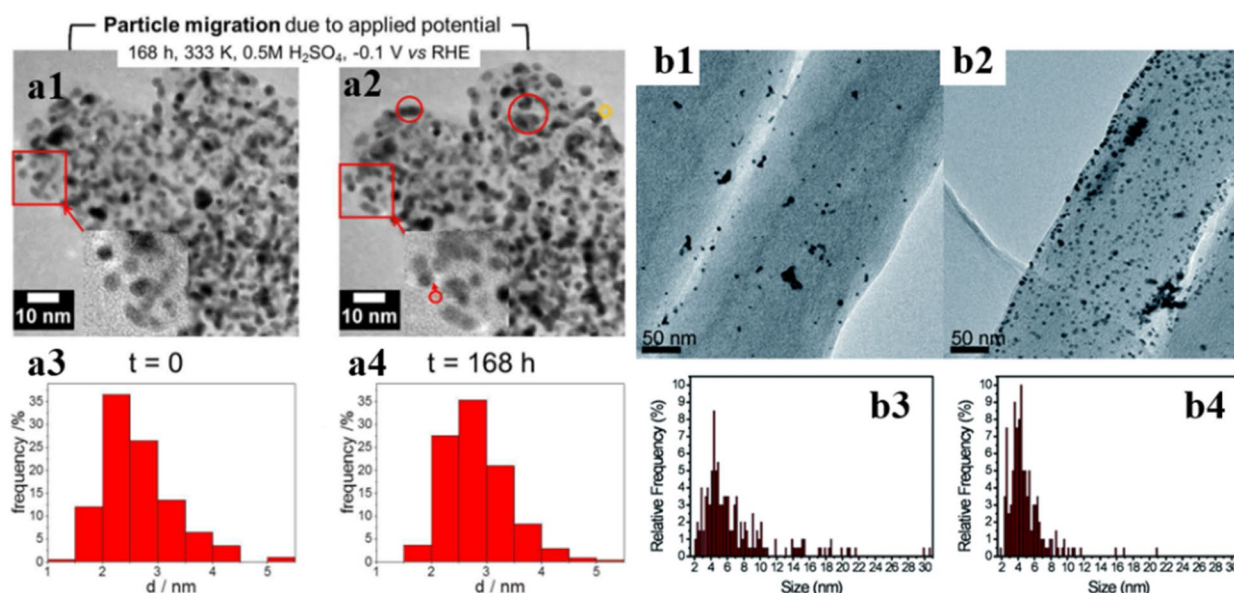


Fig. 5 **a** Identical location TEM images and particle size distributions of Pt/C cathode catalyst before (a1, a3) and after 168 h CA test (a2, a4). [37] Copyright 2017, Elsevier. **b** TEM images and particle size distributions of Pt cathode catalysts on carbon nanofiber substrate without (b1 and b3) and with the deposition of SiO₂ (b2 and b4) after 10,000 CV cycles test. [38] Reproduced under the terms of the IEA. CC BY 3.0. license. Copyright 2015, Royal Society of Chemistry

Pt active sites, making it crucial to select an appropriate coating thickness to balance activity and stability [39].

2.1.4 Active site blockage

Active site blockage in electrocatalysts refers to the phenomenon where catalytic sites on the surface of a catalyst become inaccessible or deactivated due to the accumulation of reaction intermediates, byproducts, or other adsorbates. These species obstruct the catalytic sites, preventing reactant molecules from accessing them during the electrochemical reaction. Hydrogen and oxygen gas bubbles generated during the reaction can adhere to the catalyst layer, particularly under high current densities, leading to active site blockage. This issue is exacerbated by the compact design of AEMWE, which features narrow flow fields and thin GDLs that make it more difficult for gas bubbles to escape from the cell [40]. Additionally, impurities or contaminants in the electrolyte or environment can deposit on the catalyst surface, causing further blockage of active sites [22]. These contaminants can bind to the catalyst surface either reversibly or irreversibly, resulting in varying degrees of catalytic activity inhibition or complete deactivation [41]. For example, a study investigating the effect of contaminants in tap water on a pure Ni rod cathode catalyst in 1 M KOH solution found that long-term CP tests in tap water showed significantly worse stability compared to pure water. SEM and EDS detected Na, S, Cl, and Fe elements on the Ni electrode surface after polarization tests in tap water. These contaminants likely blocked the active sites of the Ni catalyst, reducing its activity [42]. The composition of the electrolyte plays a crucial role in mitigating catalyst poisoning and must be carefully controlled. For instance, carbonates like K_2CO_3 , formed from the reaction of KOH with CO_2 in the air, are either insoluble or only slightly soluble in alkaline electrolyte solutions. This reaction not only consumes OH^- ions but also leads to the formation of deposits that can overlay or clog the catalyst surface, inhibiting electrolyte contact and hindering hydroxide ion diffusion, which reduces device performance [43].

Optimizing the ionomer content in the catalytic layer is essential for maintaining stability and conductivity while minimizing active site coverage, which is critical for AEMWE performance [44]. Effective gas expulsion is crucial for maintaining catalyst accessibility, facilitating continuous electrochemical reactions, and maximizing catalyst utilization. Incorporating innovative gas bubble release techniques could accelerate the evaporation of gases. For example, a superaerophobic (i.e., the adhesion between bubble and electrode is low) MoS_2 electrode surface with a nanoporous structure showed better bubble release compared to a flat surface, owing to its lower adhesion force with bubbles [45]. Optimization of the

design of the electrolysis cell, particularly the GDL, to promote gas release was also a powerful method, which will be discussed in detail in Sect. 4.

2.2 Catalyst reconstruction

The reconstruction of catalysts during operation, which involves localized changes in composition, crystal structure, and electronic configuration [27], significantly impacts intrinsic catalytic activity [46, 47]. This phenomenon is especially pronounced in non-precious metal OER catalysts when operating in KOH electrolytes, where the reconstructed form is often considered the real active species. For instance, transition metal oxide catalysts typically undergo reconstruction into (oxy)hydroxide compounds. This reconstruction is a dynamic process that affects the catalyst's physicochemical properties, including its composition, structure, and electronic configuration.

The impact of in-situ reconstruction on catalyst stability is complex and varies with catalyst material and operating conditions. For example, the in-situ reconstruction of LiCoO_2 into a spinel LiCo_2O_4 -type structure was shown to reduce OER stability due to the formation of unstable Co^{4+} ions. However, Cl doping redirected the reconstruction pathway of $\text{LiCoO}_{1.8}\text{Cl}_{0.2}$, forming active Co (oxy)hydroxide and avoiding Co^{4+} , which simultaneously enhanced both OER activity and stability (Fig. 6a) [48, 49]. A systematic study of NiFe and NiCo bimetallic alloy catalysts revealed that during OER in 1 M KOH solution, a core-shell structure forms. The surface of the catalyst transforms into an amorphous (oxy)hydroxide phase, while the initial bulk alloy phase remains as the core. The amorphous oxyhydroxide layer acts as a protective barrier, minimizing the degradation of the underlying alloy core. This layer helps resist corrosion and structural breakdown during prolonged electrochemical reactions. Meanwhile, the crystalline alloy core provides mechanical strength and stability, supports the overall structure, and facilitates efficient charge transfer, reducing charge accumulation at the catalyst surface and preventing potential-induced degradation. The strong adhesion between the core and shell layers ensures the catalyst remains intact even under high current densities with significant gas evolution, allowing the core-shell heterostructure catalysts to operate steadily at 1 A/cm² for over 300 h without noticeable degradation [50].

Conversely, uncontrolled reconstruction can lead to structural degradation and material loss, impacting long-term stability [47]. Recent studies have proposed that during OER, the lattice oxygen evolution reaction—which involves the oxidation of lattice oxygen—facilitates dynamic restructuring of the catalyst surface into a self-assembled metal oxy(hydroxide) layer. However, this

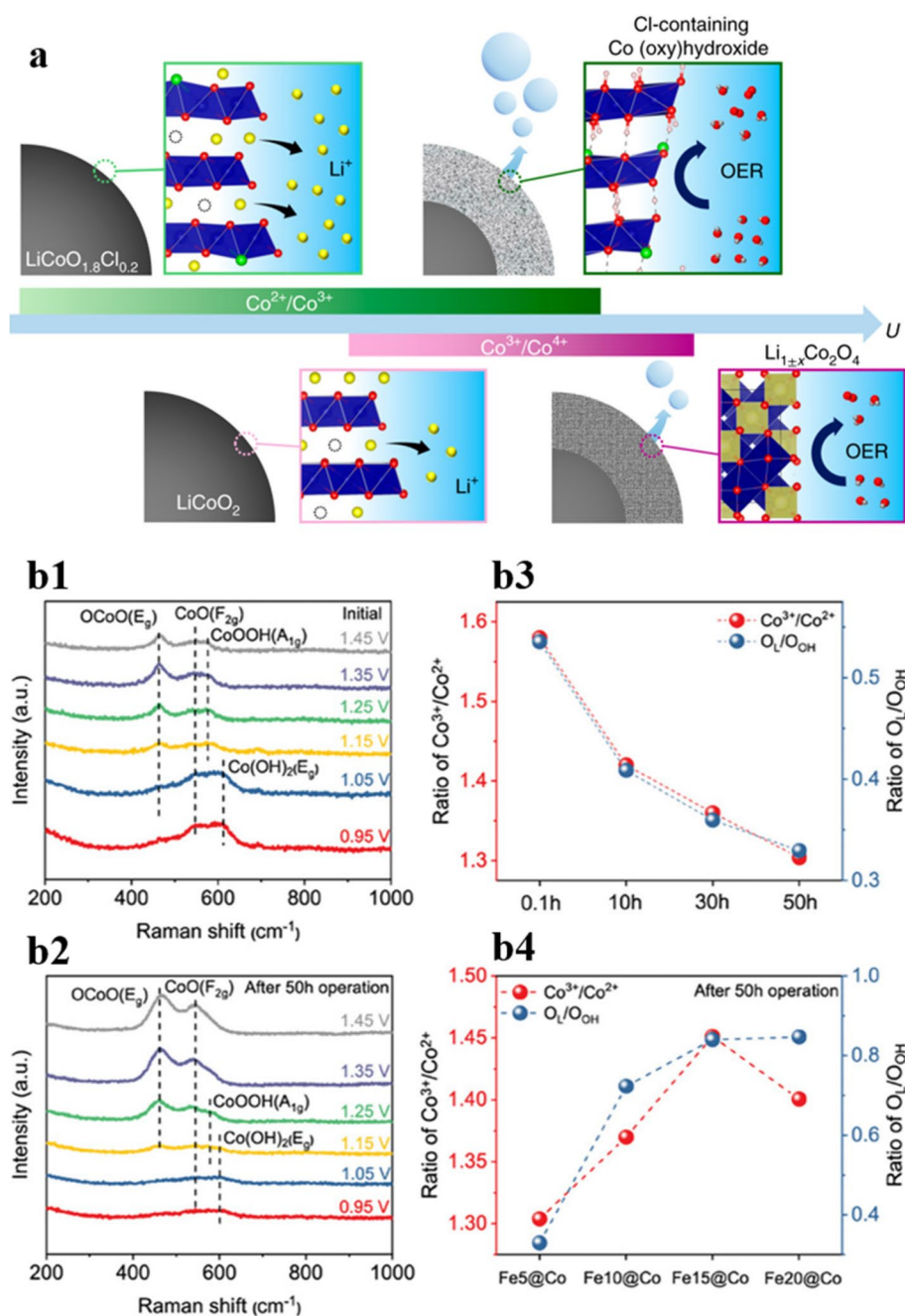


Fig. 6 **a** Schematic diagram of the reconstruction of LiCoO_2 and $\text{LiCoO}_{1.8}\text{Cl}_{0.2}$ as anode catalyst [48]. Copyright 2021, Springer Nature. **b** in-situ Raman spectra of Fe@Co as the anode catalyst at pristine (b1) and after 50 h stability test (b2). Evolution $\text{Co}^{3+}/\text{Co}^{2+}$ and O_L (lattice oxygen)/OOH ratios of Fe@Co catalyst (b3) and the influence of Fe content on the $\text{Co}^{3+}/\text{Co}^{2+}$ and O_L/OOH ratios after 50 h stability tests according to XPS [53]. Copyright 2024, John Wiley and Sons

lattice OER process can also result in the dissolution of metal cations (for example, Co [51] and Ni [52]) from the catalyst structure, reducing the number of active sites and decreasing activity. Sanghwi Han et al. investigated the reconstruction of Co_3O_4 ($\text{Co}^{2+}/\text{Co}^{3+}$) into CoOOH (Co^{3+}) in Fe@Co catalysts during operation at $0.5 \text{ A}/\text{cm}^2$

in AEMWE. They found that increasing the cell voltage of the AEMWE single cell was accompanied by a decrease in the number of active Co^{3+} (CoOOH) sites and lattice oxygen content, as confirmed by in-situ Raman spectroscopy (Fig. 6b1 and 6b2). The authors suggested that adjusting Fe electrodeposition could preserve the active

CoOOH species and enhance the overall durability of the AEMWE devices (Fig. 6b) [53]. However, further investigation is needed to fully understand the underlying mechanisms.

Currently, most research concentrates on developing highly active catalysts through controlled reconstruction processes. However, there is limited investigation into how catalyst reconstruction affects stability, especially under the demanding conditions of AEMWE, such as high current densities and elevated temperatures [47]. To address this, it is essential to gain a thorough understanding of the dynamic reconstruction processes of catalysts and to achieve a balance between high activity and stability through rational reconstruction control.

3 Degradation of ionomer binders and membranes

Incorporating catalysts onto conductive substrates via adhesive binders could enhance stability by preventing active material from falling off and maintaining the activity by conducting electrons and ions efficiently [54]. However, the adhesion strength typically diminished under high operating current densities and flushing electrolytes, leading to catalyst detachment from the substrate and consequently shortening the electrode lifespan in AEMWE [55]. The binder and membrane used in an AEMWE were often the same or similar materials. AEM played several crucial functions in an AEMWE device such as ion transport, electrolyte/gas separation, water management, and mechanical support for catalysts, all essential for maintaining the stability and efficiency of the electrolysis process. The ionomer material has undergone several iterations across multiple generations and currently, commercial products such as Fumasep FAA3-50, Sustainion, Aemion™, and PiperION™ are available [20]. However, the technology readiness of anion exchange ionomers still could not compete with proton exchange ionomers in terms of efficiency and life.

3.1 Mechanical failure

The mechanical failure of the ionomer binder can be attributed to cycles of swelling and shrinkage due to hydration and dehydration during operation. Additionally, excessive gas generation at the interface between the catalyst and binder under high current conditions induces mechanical stresses within the ionomer. These stresses can lead to fatigue and eventual failure, manifested as cracking or delamination from the electrode surfaces. The mechanical deformation or damage to the ionomer could further impair its ion conductivity [56]. The intrinsic binding capability of the ionomers is also critical for strong adhesion. Electrochemical analyses, combined with molecular dynamics and DFT

calculations, revealed that the quaternized polycarbazole-trimethylamine ionic group exhibited weak adhesion to oxygen atoms in IrO₂. This weak adhesion led to the rapid initial failure of AEMWE during constant current tests. In contrast, the polarized sulfonic acid group in Nafion formed a strong bond with catalyst particles, significantly enhancing device stability. [57].

The membrane in an AEM-based device is subjected to various stresses, including those from assembly, hydration/dehydration cycles, electrolyte flushing, and the buildup of pressured gas over time. These stresses can lead to increased gas crossover, reduced ion conductivity, and decreased overall performance of the device. As shown in Fig. 7a, such stresses caused significant membrane deformation (Fig. 7a2 and a3) and increased the MEA voltage from 1.69 V to 2.12 V after a 12-hour chronopotentiometry (CP) stability test at 0.5 A cm⁻² (Fig. 7a1) [57]. AEMs typically swell upon hydration and shrink during dehydration. While some swelling is beneficial for enhancing ion transport, excessive swelling can cause membrane deformation or mechanical failure [58, 59]. Hence, controlling hydration levels is crucial for maintaining optimal membrane performance. For example, aminated tetramethyl polyphenylene-based AEMs showed that a membrane at 95% humidity had a strength of only 25 MPa compared to 70 MPa for its dry counterpart. However, the fracture strain of the dry membrane was about 30%, half that of the humid membrane, as depicted in Fig. 7b [60]. Under pressurized conditions, while overall efficiency may improve, additional strain is imposed on the membrane, and hydrogen-oxygen crosstalk can become more pronounced. Membrane puncture, potentially leading to short circuits, can occur due to improper assembly clamp force, methods, or sharp protrusions from the GDL or catalyst layer [11]. Moreover, alkaline electrolytes can weaken the membrane's toughness and cause fatigue, further compromising its structural integrity and barrier properties [61]. The high operating temperatures (60–90 °C) designed to enhance electrochemical kinetics can also increase the membrane's creep tendency, making it more prone to physical damage or deformation [62]. This damage could compromise the sealing integrity and lead to leaks or inefficiencies in the device [63].

The strength of the polymer backbone plays a crucial role in determining the overall strength of the membrane [64]. Crosslinking the backbone structure enhances the mechanical strength of polymers by forming a three-dimensional network. This network restricts polymer chain mobility, distributes stress more evenly, and prevents plastic deformation, resulting in improved tensile strength, toughness, and dimensional stability. For instance, crosslinked poly(styrene-ethylene/

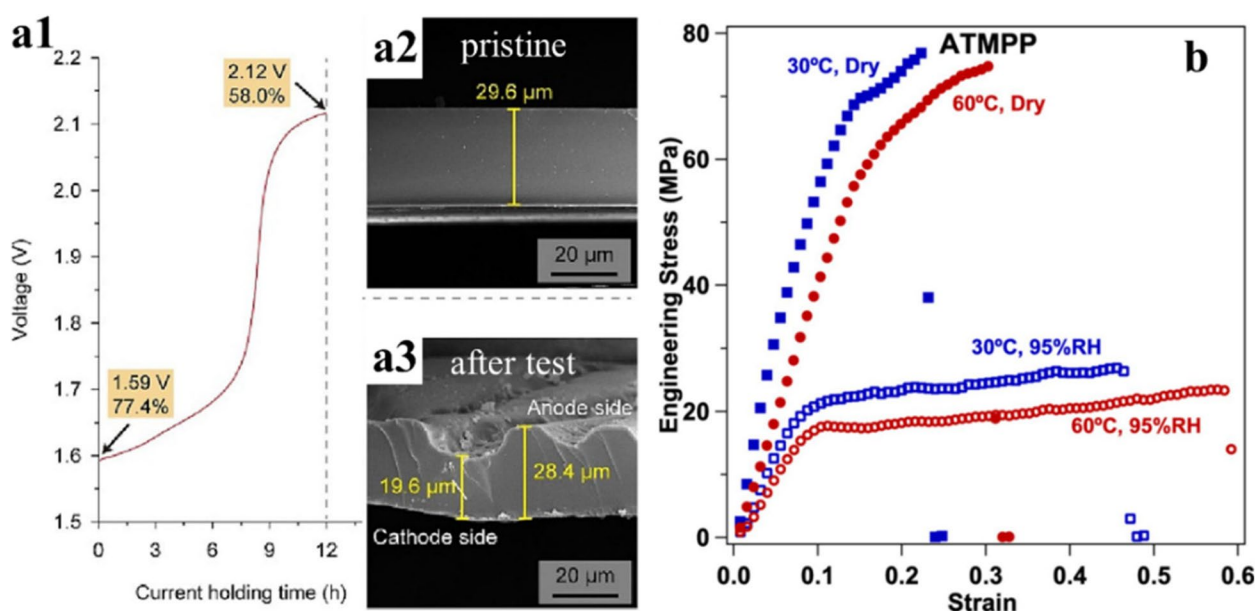


Fig. 7 **a** Voltage profile (a1) and SEM images of the AEMWE with anion conducting ionomer material (poly(9-(6-(trimethylammonium)hexyl)-9H-carbazole-co-1,1,1-trifluoroisopropane) before (a2) and (a3) after CP stability test for 12 h @0.5 A cm⁻². [57] Copyright 2023, Elsevier. **b** the engineering strain-stress curves of the aminated tetramethyl polyphenylene membrane at different temperatures (30 and 60°C) and humidity (30% and 95%) [60]. Reproduced under the terms of the IEA. CC BY 4.0. license. Copyright 2014, The Author(s)

butylene-styrene)-based AEMs exhibited a substantial increase in tensile strength from 4.00 MPa to 18.43 MPa, while maintaining high ionic conductivity due to effective hydrophilic/hydrophobic phase separation [65]. The length and position of grafted side chains also significantly impact the mechanical strength of the ionomer. Membranes with side chains linked to the fluorene monomer demonstrated remarkable improvements in mechanical strength, dimensional stability, and electrochemical performance. These membranes achieved a tensile strength exceeding 60 MPa and a Young's modulus over 1000 MPa, attributed to the enhanced structural integrity provided by the fluorene-linked side chains [66]. Additionally, research has shown that increasing the size of cation groups can enhance the mechanical strength of membranes, though this often reduces flexibility. For example, membranes with larger cations such as imidazolium exhibited a higher Young's modulus and lower elongation at break. These membranes also displayed higher water uptake while maintaining good hydroxide conductivity and stability [67].

3.2 Chemical degradation

The stability of binders in alkaline conditions is largely determined by the nature of their cationic groups, which include imidazolium, phosphonium, ammonium, sulfonium, and metal-based cations. Exposure to alkaline conditions during electrolysis can cause hydrolysis of

the ionomer, leading to cleavage of polymer chains. This degradation process is exacerbated at elevated temperatures and high pH levels, resulting in a loss of mechanical strength and structural integrity of the ionomer material.

Yang et al. systematically explored the chemical stability of various cationic groups in alkaline environments. For instance, tetraalkylammonium cations with trimethylammonium groups appended via an alkyl linker generally undergo SN₂ demethylation, as shown in Fig. 8a2. In contrast, trimethylammonium cations positioned at a benzylic site are prone to SN₂ attacks at the benzylic carbon (Fig. 8a1). Quaternary ammonium cations with substituents bearing beta hydrogens to the nitrogen may experience Hofmann elimination (Fig. 8a3). Additionally, cyclic ammoniums can undergo SN₂ attacks at the α-carbon relative to the nitrogen atom (Fig. 8a4) or Hofmann elimination, leading to ring opening (Fig. 8a5) [68].

The stability of polymer backbones is crucial for the longevity of membranes used in electrochemical devices. Certain polymers, such as poly(aryl ether sulfone)s, poly(phenylene oxide)s, and poly(ether ketone)s, are prone to rapid degradation due to aryl ether cleavage reactions in alkaline environments [68]. MEAs utilizing membranes with stable backbones tend to exhibit longer lifetimes compared to those with unstable backbones. For instance, MEAs incorporating alkaline-stable backbones, such as benzyl trimethyl ammonium-functionalized Diels-Alder polyphenylene, show significantly longer

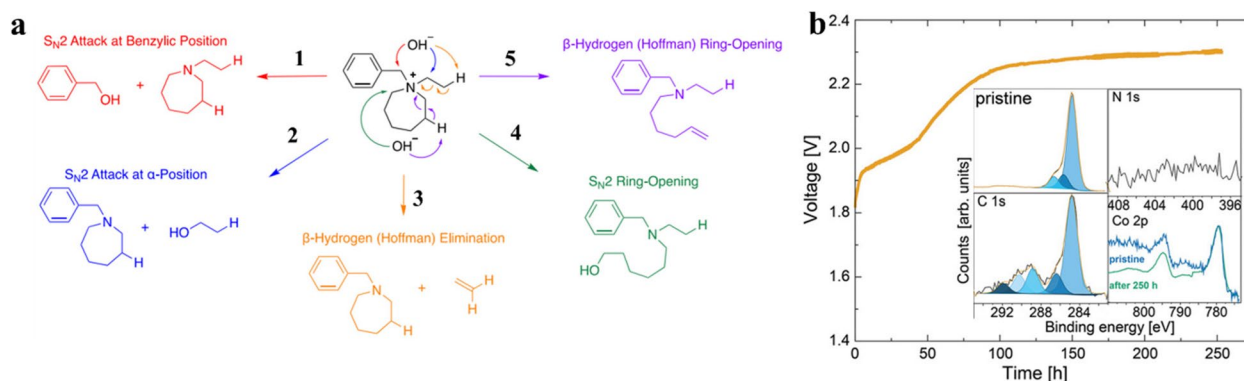


Fig. 8 **a** Degradation pathways for tetraalkylammonium cation groups [68]. Copyright 2022, American Chemical Society. **b** XPS results showed severe oxidation of the PiperION ionomer after 250 h stability test [69]. Copyright 2022, John Wiley and Sons

lifetimes than those using alkaline-unstable partially fluorinated poly(arylene ether)s backbones [70].

A comprehensive DFT study highlighted that, in high-pH alkaline solutions, polybenzimidazole membranes deprotonate to form ionized species, with the loss of two protons being predominant. Degradation likely starts with hydroxide ion attack on the carbon in polybenzimidazole and the deprotonated species. This process is followed by a ring-opening reaction involving hydroxyl proton transfer, C-N bond breaking, and stabilization of the N dangling bond. Hydroxide ions or water molecules might facilitate this proton transfer. The ring-opening reaction creates an amide linkage that undergoes alkaline hydrolysis, leading to complete chain scission. These findings offer valuable insights into the main degradation pathways of polybenzimidazole membranes in alkaline solutions and emphasize the need to consider explicit water molecules in computational studies [71].

Additionally, the attack of oxygen or hydroxyl radicals on the methyl group of rearranged ylides can form aldehyde or carboxyl groups, which may contribute to the degradation of quaternized poly(p-phenylene oxide)-based membranes in both pH-neutral [72] and alkaline media [73]. These insights are crucial for designing degradation-resistant AEMs for alkaline water electrolyzers and fuel cells. Optimizing the polymer structure, particularly for polybenzimidazole membranes, could further enhance their alkaline stability [74].

Electrochemical processes at the electrode interfaces can significantly contribute to the degradation of the ionomer binder. Reactions such as the oxidation or reduction of functional groups within the binder material lead to structural changes and performance loss. For instance, XPS results revealed that the PiperION Versogen ionomer underwent substantial oxidation after just 20 h of operation, with further damage evident in the C 1s region after 250 h of operation in AEMWE. As shown

in Fig. 8b, the appearance of new peaks at high-energy regions of the C 1s XPS spectrum after the stability test compared to the pristine ionomer indicated severe oxidation [69].

The electrochemical oxidation of phenyl groups in ionomers typically occurs at potentials above 0.6 V versus RHE [54]. This process leads to the formation of phenol, as confirmed by ^1H nuclear magnetic resonance spectroscopy, with the oxidation rate increasing at higher cell potentials [75]. The degradation of phenyl-containing ionomers notably impacts AEMWE performance. Phenol formation alters the local pH at the electrodes, which adversely affects the OER [76]. A comparison of ionomers with varying phenyl adsorption energies showed that those with higher phenyl adsorption energies experienced a gradual increase in cell voltage over time due to phenyl oxidation, whereas those with lower energies remained more stable [21]. Even phenyl-free ionomers undergo electrochemical degradation under high pH conditions [77].

The chemical stability of anion exchange ionomers or membranes is largely influenced by their functional groups. Consequently, most research has focused on modifying these functional groups to enhance chemical stability [78]. For example, the ethyl ammonium functional group improves chemical stability by reducing water uptake. Its hydrophobic nature limits excessive swelling and hydration, helping to maintain the membrane's structural integrity. This reduction in water uptake prevents over-expansion and potential degradation in alkaline environments, making ethyl ammonium functionalized polymers more stable compared to those with more hydrophilic groups like methylammonium [79]. Additionally, nickel-based metallopolymers synthesized with mono-, bi-, and tri-pyridine ligands have been evaluated for their chemical stability under harsh alkaline conditions. Testing in 3 M NaOH and 0.5 M KOH

solutions revealed that the alkaline stability of these polymers correlated with ligand coordination. Higher coordination numbers contributed to increased stability under alkaline conditions [80].

3.3 Contamination

Interaction with catalyst materials in AEMWE electrodes can lead to the degradation of the ionomer binder. This degradation often manifests as the adsorption of catalyst species onto the ionomer surface, obstructing active sites and disrupting ion transport properties. The negatively charged surfaces of catalysts attract cationic moieties in the ionomer, impeding both catalytic activity and ion transport. This interaction not only leads to structural deterioration of the ionomer but also results in reduced HER performance in AEMWE devices [81].

Impurities in the electrolyzer device significantly impact membrane stability. For example, cationic impurities in the water can compromise membrane water transport properties and overall stability, while also catalyzing harmful side reactions. This reduces both membrane performance and lifespan [22]. Another issue is carbonation, which increases area-specific resistance and decreases water uptake and permeability, further affecting ionomer degradation. Additionally, cationic degradation products from the ionomer may form carbonate salts, further impacting device performance [82]. The ionomer may also undergo oxidation into fragments during electrolysis in a K_2CO_3 electrolyte, leading to the rapid failure of AEMWE [83].

Current research on anion exchange ionomers aims to enhance mechanical and chemical stability to improve performance in practical applications. Mechanical stability is being addressed through crosslinking and optimizing cation group-backbone designs to strengthen the membrane structure. For chemical stability, effective strategies include modifying functional groups with bulky and electron-donating substituents, adding alkyl spacers, and using stable polymer backbones such as poly(phenylene) and poly(phenylene oxide). Despite these advancements, challenges persist, including balancing conductivity and stability, managing excessive water uptake that causes mechanical deformation, and the incomplete understanding of degradation mechanisms. To address these issues, future research should focus on optimized functional group designs, advanced composite membranes, precise crosslinking techniques, and comprehensive degradation studies. Emerging directions include exploring new functionalization chemistries, employing high-throughput screening methods like molecular dynamics and machine learning, and developing eco-friendly materials.

4 Degradation of gas diffusion layer

GDL are critical components in AEMWE. They facilitate the transport of reactants and products—such as water and gas bubbles—to the catalyst layer, enable electron transfer between the membrane electrode and current collector, and provide mechanical support. Positioned in direct contact with the catalyst layer, current collector layer, and electrolyte, the GDL plays a pivotal role in ensuring effective transport and facilitating proper contact between different device components. To fulfill these functions, GDL materials must possess specific properties, including excellent conductivity, durability, and chemical stability in alkaline environments. These characteristics are essential for maintaining the efficiency and longevity of the electrolyzer [84].

At the cathode end of AEMWEs, the alkaline environment is less corrosive compared to the acidic environment of PEMWE. This allows for the use of cost-effective stainless steel materials as the GDL [85]. Conversely, carbon-based materials such as carbon paper, carbon cloth, and carbon felt are commonly employed at the cathode due to their high electrical conductivity and corrosion resistance. Additionally, carbon-based GDLs are lightweight and economical, making them suitable for large-scale electrolyzer deployments.

4.1 Mechanical degradation

In AEMWE, clamping force is typically applied to reduce the contact resistance between components and prevent electrolyte and gas leakage, ensuring operational safety. The GDL often features a porous structure to facilitate efficient material transfer. However, this porous structure can deform under clamping force and, in severe cases, may even break, leading to poor material transfer and reduced cell performance [86].

Mechanical degradation is particularly severe for brittle GDL materials, such as carbon paper. As illustrated in Fig. 9a, clamping force can cause the fibers of the GDL to break and destroy its porous structure. This damage compromises the hydrophobic surface and disrupts the transport of reactants and products [87]. Additionally, operational stresses from temperature fluctuations or pressure changes within the electrolyzer can further strain the GDL over time. Continuous mechanical stress may result in cracking or alterations in the GDL's porosity, compromising its functionality.

Changes in the porous structure of the GDL significantly impact AEMWE performance. For example, a decrease in throat diameter (the average distance between adjacent fibers) and pore-throat diameter ratio can increase gas bubble entrapment within the electrode. This trapped gas reduces the effective surface area available for the OER, ultimately leading to

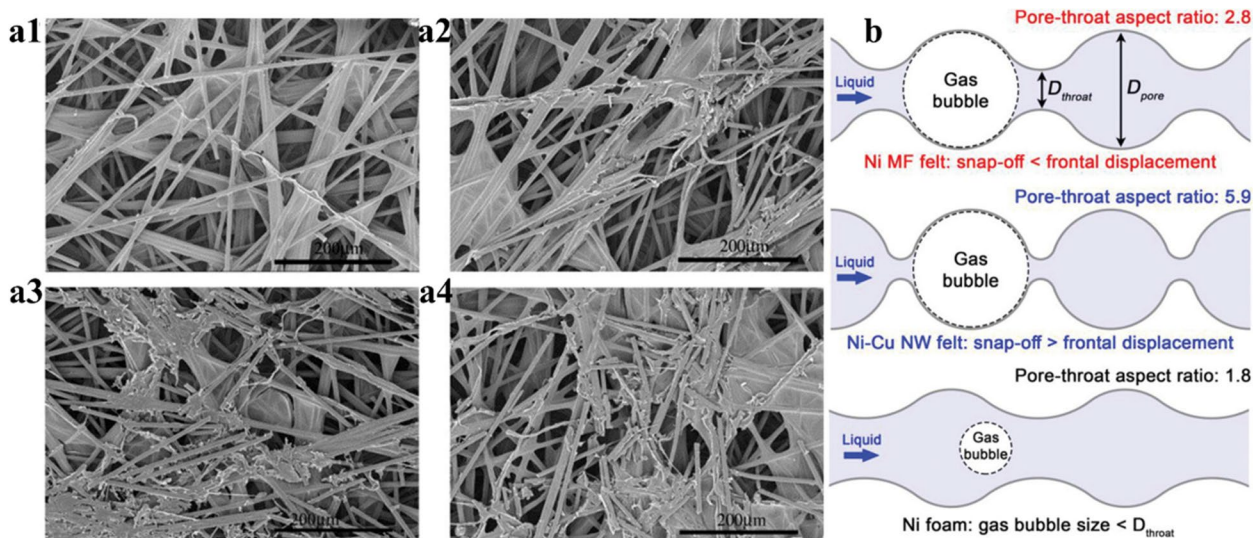


Fig. 9 **a** SEM images of compression effect on the structure of carbon paper GDL after compressed at (a1) 0.18 MPa, (a2) 0.36 MPa, (a3) 0.68 MPa, and (a4) 1.37 MPa [87]. Copyright 2007, Elsevier. **b** Trapping effect on gas bubbles of GDL with different structures [88]. Copyright 2020, John Wiley and Sons

decreased performance. (Fig. 9b) [88] Compared to steady loading, the deformation of Toray carbon paper GDLs increased during cyclic loading, which compacted the fiber microstructure and potentially affected the transport of water and gases [89].

Maintaining the integrity of the GDL is crucial for stable AEMWE operation. Optimal clamping pressure is needed to balance pore structure preservation with contact resistance [90]. This value is not universal and must be determined based on specific cells, materials, and structures. Different GDL configurations exhibit varying mechanical stabilities. Carbon felt GDLs, with their thicker and more tortuous fibers, show greater resilience compared to carbon paper and carbon cloth. The robustness of carbon-felt GDLs helps distribute pressure more evenly, preventing significant deformation. In contrast, carbon paper, with its delicate structure, and carbon cloth, despite its woven fibers, are more prone to damage under higher pressures [89].

Therefore, selecting appropriate GDL materials and maintaining compression pressure below critical thresholds are essential for preserving cell performance. Novel GDL designs, such as optimized pore size, porosity, and hierarchical pore structures, can enhance mechanical properties [91]. However, complex structures often involve more challenging processing routes and higher costs. Thus, developing cost-effective and robust GDL structures is crucial for facilitating the commercialization of AEMWEs.

4.2 Chemical degradation

Chemical degradation of the GDL in AEMWE involves the deterioration of GDL materials due to chemical reactions and environmental conditions. A significant degradation mechanism is electrolysis-induced oxidation, where the GDL material undergoes oxidative reactions due to exposure to highly reactive oxygen species generated during electrolysis.

Although the alkaline environment at the anode of AEMWE is less corrosive than the acidic environment at the anode of PEMWE, materials such as SUS304L stainless steel still experience corrosion in alkaline electrolytes. Research has shown that Fe oxides on the surface of SUS304L stainless steel dissolve during electrolysis, forming Fe ions. These ions react with hydroxide ions present in the solution to produce $Fe(OH)_2$, which appears as hydroxides on the surface after electrolysis. This process not only deteriorates the material but also increases the contact resistance of the stainless steel GDL, reducing the efficiency and performance of the AEMWE device [92].

Few studies have focused on enhancing the corrosion resistance of GDLs in AEMWE. Nonetheless, corrosion remains a significant issue since dissolved Fe ions might react with the catalyst, ionomer, or membrane, affecting overall performance. One potential solution is to apply a protective coating, such as titanium (Ti), on the stainless steel GDL. Ti coatings have demonstrated effectiveness in increasing corrosion resistance in PEMWE devices and could offer valuable insights for AEMWE GDL

design [93]. However, the high cost of Ti coating poses a challenge, raising concerns about its economic feasibility for industrial applications. The decision to use such coatings involves evaluating the trade-off between improved performance and longevity against increased costs, considering factors such as specific application, expected operational lifespan, and overall device cost.

In contrast, the chemical degradation of carbon-based GDLs is less frequently discussed, primarily because these materials are typically used in the cathode's reduction environment, where carbon materials are chemically stable. Consequently, their degradation is minimal compared to materials exposed to oxidative environments at the anode.

5 Interface degradation

In addition to the degradation of individual components, the interfaces between these components also represent significant sources of degradation. In an AEMWE device, several interfaces are critical, including the catalyst/ionomer binder interface, catalyst layer/electrolyte interface, AEM/catalyst layer interface, catalyst layer/GDL interface, and GDL/flow field interface. These interfaces are pivotal in determining the performance and efficiency of AEMWE devices. Most reactions and processes—including charge transfer, mass transport (encompassing ions, gases, and water), adsorption, desorption, and mechanical adhesion—occur at these interfaces. Therefore, understanding the mechanisms by which these interfaces may deactivate or fail during operation is crucial for the effective design and assembly of AEMWE devices.

5.1 Increased resistance

In addition to the degradation mechanisms affecting individual components discussed earlier, the deterioration of various interfaces significantly impacts the performance of AEMWE devices. The failure of the catalyst layer/AEM interface is primarily attributed to factors such as the loss of binder adhesion, excessive membrane swelling, and the accumulation of gas bubbles at the surface. Operational stresses, including mechanical strain from swelling/shrinkage cycles and thermal stress from elevated temperatures, further exacerbate interface degradation in AEMWE devices. For instance, the catalyst layer/AEM interface in an AEM-fuel cell has been observed to fracture due to the deformation of the AEM during operation, as shown in Fig. 10a. The detachment between the two layers becomes more pronounced as the operating temperature increases from 60 °C to 70 °C, leading to higher charge and ion transfer resistance [94]. Additionally, gas bubble accumulation contributes to the failure of the catalyst layer/membrane and catalyst layer/GDL interfaces. High current densities

and applied voltages raise local temperatures and widen water channels within the membrane, facilitating oxygen permeation and causing membrane thinning. This, combined with shortened step durations in cycling protocols, affects bubble nucleation, growth, and detachment, further exacerbating membrane/catalyst interface degradation [95]. Poor contact at these interfaces significantly increases interface resistance, translating into higher overpotential requirements for electrolysis and ultimately diminishing the efficiency of the electrolyzer.

Enhancing interface contact and reducing resistance for efficient charge and ion transfer across interfaces are essential for improving the overall efficiency and effectiveness of AEMWE devices. The delamination issue at the catalyst layer/AEM interface can be addressed using a novel ionomer employing a thermally triggered covalent-locking strategy. This approach creates a stable three-dimensional interface between the AEM and covalent-locking agents, thereby enhancing mechanical stability. Ex-situ shear tests have confirmed improved interfacial bonding, while in-situ electrochemical impedance spectroscopy (EIS) has demonstrated sustained integrity during cell operation, even under high current densities and gas humidity cycling. The resulting three-dimensional-zipped interface prevents delamination, ensuring efficient ion and reactant transport within the cell [94]. Rational design of electrode structures, such as self-supported electrodes [96], optimization of GDL structures with hierarchical pore arrangements [97], and improvements in flow field designs [98] are necessary to promote gas detachment from surfaces and facilitate transport through various interfaces. For example, AEMWE with self-supported $\text{Fe}_{0.2}\text{Ni}_{0.8}\text{-P}_{0.5}\text{S}_{0.5}$ electrodes exhibits superior stability compared to those with PT/C/IrO₂ electrodes due to increased hydrophilicity resulting from the nanoarrays configuration, as shown in Fig. 10b. These measures are crucial for the stable and efficient operation of large-scale AEMWE devices, ultimately advancing their industrialization.

5.2 Decreased mass transfer

The mass transfer capability in AEMWE devices is significantly influenced by the interface environment. Efficient ion transport, essential for AEMWE functionality, relies on the effective movement of anions (such as OH⁻) across the AEM to the electrode surfaces where water electrolysis occurs. Research indicates that in alkaline conditions, the interfacial water network becomes more rigid and less amenable to reorganization due to stronger interactions with the electric field, which slows down the HER process. This rigidity complicates the reorganization of water molecules during charge transfer through the electrical double layer at the catalyst layer/

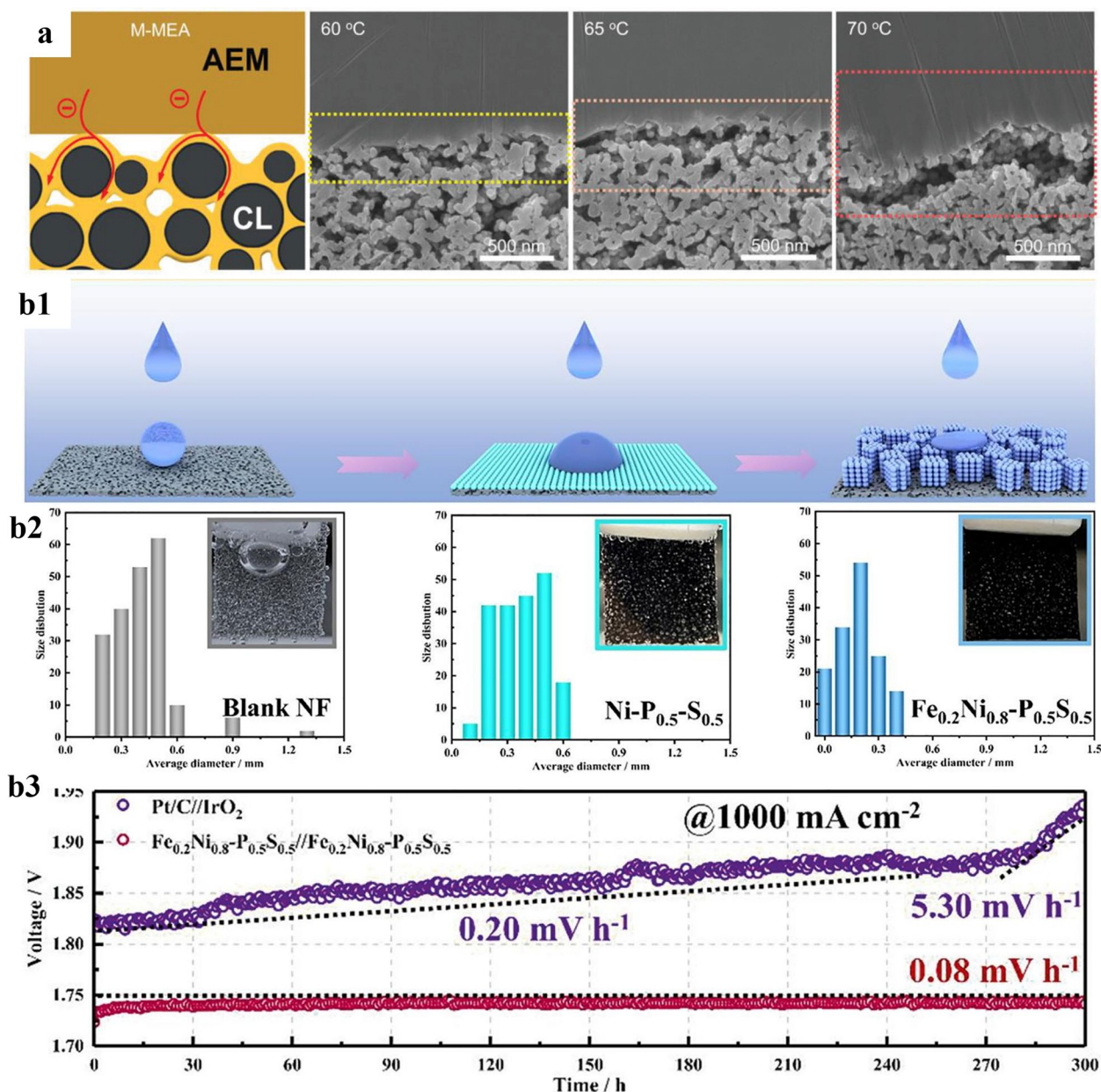


Fig. 10 **a** Schematic diagram of the OH⁻ transportation between catalyst layer/AEM interface and the cross-section SEM images of the cathode catalyst layer/AEM interface after operation at 60, 65, and 70 °C. [94] Reproduced under the terms of the IEA. CC BY license. Copyright 2021, The Author(s). **b** Schematic diagram of the increasing hydrophilicity of the self-supported Fe_{0.2}Ni_{0.8}-P_{0.5}S_{0.5} nanoarrays anode electrode compared to bare Ni foam substrate (b1), the measured diameter distribution of gas bubbles (b2) and the superior stability of electrolyzer with the self-supported electrode compared to that with Pt/C/IrO₂ electrodes (b3) [96]. Copyright 2022, Elsevier

electrolyte interface, thereby impeding the efficiency of proton/hydroxide transfer necessary for the HER [99]. The presence of Ni(OH)₂ in submonolayer quantities has been shown to mitigate this issue by facilitating the reorganization of the interfacial water network, leading to more efficient proton/hydroxide transfer through the

double layer and enhancing HER kinetics under alkaline conditions.

Gas bubbles generated at the electrode surfaces and within the porous electrode during electrolysis further exacerbate resistance within the device and obstruct mass transfer at the interface, adversely affecting the stable operation of AEMWE. [23, 100] Effective regulation

of gas evolution through the design of superaerophobic catalyst surfaces has proven successful in accelerating gas bubble release at interfaces and promoting electrochemical reactions [101].

The performance of AEMWE devices is largely dependent on the functionality of interfaces throughout the electrolysis process. However, these interfaces are susceptible to degradation over time due to various stressors, including chemical, mechanical, and electrochemical factors. Therefore, ensuring the stability and durability of these interfaces is crucial for maintaining the long-term performance and reliability of AEMWE devices.

6 Conclusions and perspectives

AEMWE technology, which merges the cost-effectiveness of AWE with the simplicity and efficiency of PEMWE, represents a promising approach for hydrogen production and achieving carbon neutrality. However, the limited stability of various components and the entire electrolyzer stack under high temperatures and alkaline conditions presents significant challenges to the development and commercialization of this technology. In this comprehensive review, we systematically examined the primary degradation mechanisms affecting critical AEMWE components, including catalysts, membranes, ionomers, GDLs, and their interfaces. We also explored strategies to enhance the stability and efficiency of AEMWEs, thereby advancing the sustainable production of hydrogen. The conclusions drawn from this review are as follows:

- 1) In AEMWE, catalysts are prone to significant degradation primarily due to the loss of active sites caused by dissolution, segregation, agglomeration, and blockage, which are exacerbated by harsh alkaline conditions and high operational voltages. Unfavorable surface reconstruction can further accelerate dissolution rates, leading to catalyst instability. Current research is focused on exploring non-precious metal alternatives, developing more robust catalyst nanostructures, applying protective coatings, and employing knowledge-driven reconstruction control to improve durability.
- 2) AEM degradation involves complex interactions between chemical attacks from hydroxide ions and mechanical stresses due to swelling and contraction during operation. These factors contribute to decreased ionic conductivity and compromised structural integrity. To enhance membrane stability, researchers are investigating advanced polymer chemistries, crosslinked structures, and composite membranes. Ionomers, crucial for ionic conductivity, face degradation mainly from chemical attacks

by hydroxide ions, which reduces conductivity and mechanical strength. Additionally, degradation at the ionomer-catalyst interface impacts overall performance. Future research aims to develop ionomers with superior chemical resistance and improved ionic conductivity, potentially through novel ionic liquids or advanced polymer designs.

- 3) GDLs undergo degradation through chemical oxidation and mechanical stress, impairing their ability to facilitate mass transport and diminishing cell performance. Efforts to enhance GDL durability include the application of protective coatings, surface treatments, and optimization of their hydrophobic properties.
- 4) The interfaces between components such as the catalyst layer, AEM, and GDL are crucial for overall performance. Degradation at these interfaces can significantly affect the efficiency and longevity of the electrolyzer. Key causes of interface degradation include increased resistance due to loss of binder adhesion, membrane swelling, gas bubble accumulation, and operational stress. These issues can lead to fracturing at the catalyst layer/AEM interface, widening of water channels within the membrane, and increased resistance. Additionally, the rigidity of the interfacial water network in alkaline conditions and the presence of gas bubbles can impede mass transfer. To mitigate interface degradation, strategies include developing advanced materials with improved stability, optimizing component designs for better gas detachment and mass transport, adjusting operating conditions to reduce interface stress, and engineering surfaces to repel gas bubbles and enhance mass transfer.

From the above, various degradation mechanisms affecting both components and interfaces contribute to the performance deterioration of AEMWEs. Despite the specific strategies discussed to mitigate these degradation issues, significant challenges remain that need to be addressed to improve the stability and performance of scaled AEMWE devices.

6.1 Optimizing operation conditions

Operational conditions, including temperature, pressure, and electrolyte composition, significantly influence the degradation of AEMWE devices. Elevated temperatures generally enhance reaction rates, thereby increasing the efficiency of the electrolysis process. Consequently, AEMWE systems are typically operated within the temperature range of 60–90 °C to optimize efficiency [19, 102]. However, high temperatures can also accelerate component degradation. For instance,

elevated temperatures can exacerbate catalyst degradation mechanisms such as agglomeration and dissolution [103]. Nonetheless, certain active substances exhibit stability at higher temperatures; for example, operating at elevated temperatures improved the longevity and efficiency of nano-NiO_x OER electrocatalyst due to favorable transformations from β-NiOOH to γ-NiOOH [104]. Temperature also affects the stability of quaternary ammonium groups in AEM, with degradation rates increasing significantly with temperature. To enhance stability, optimizing molecular structures, such as using aliphatic rather than benzylic or aromatic ammonium groups, and incorporating spacer chains and heterocyclic structures can minimize reactive sites, provide steric hindrance, and inhibit common degradation pathways like β-elimination and nucleophilic substitution [105]. Furthermore, temperature impacts the strength of interactions between the catalyst layer and the membrane. For instance, the peeling strength of x-PDTP-Pr-50 (AEM) and x-Trip-PFBP-Pr-30 (Ionomer)-based MEA decreased from 0.395 N mm⁻¹ at ambient conditions to 0.226 N mm⁻¹ at 80 °C, indicating that higher temperatures can weaken these interactions [106]. Elevated temperatures also result in smaller, more easily detached O₂ gas bubbles and reduced solution resistance due to increased ionic species diffusivity and improved overall reaction kinetics. Overall, the effect of operational temperature on AEMWE stability is complex, and its impact on various components must be considered when determining the optimal operating temperature.

The optimal clamping pressure for AEMWE devices typically ranges from 1.5 to 3.0 MPa, depending on factors such as membrane properties, catalyst characteristics, GDL specifications, MEA assembly methods, and desired hydrogen output pressure. Proper clamping pressure maintains the structural integrity of components such as the gas diffusion layer, electrodes, and membrane, ensuring effective contact between components to reduce contact resistance and enhance charge transfer. Consistent pressure also supports uniform current distribution across electrodes, contributing to stable electrochemical performance. Excessive pressure can cause detrimental effects, including gas crossover, membrane puncture, compression of the catalyst and GDLs, and issues with mass transport of water and gas [107]. Conversely, insufficient pressure can lead to poor component contact, mechanical instability, and uneven electrolyte distribution, all of which compromise cell stability. Hydraulic clamping offers a promising solution due to its adjustable clamping force and ability to maintain constant and uniform pressure, surpassing the limitations of conventional mechanical compression methods [108].

The choice of electrolyte for AEMWE devices varies based on specific application requirements. Compared to pure water, KOH and K₂CO₃ solutions offer higher ion concentrations, reducing ion conductivity resistance within the device and thus improving activity and durability [109]. However, the corrosive nature of alkaline electrolytes presents challenges for materials used in AEMWE devices. Components such as membranes, catalysts, ionomers, and GDLs may be susceptible to corrosion over time when exposed to alkaline electrolytes. For example, neutral or mildly alkaline conditions can result in poorer stability due to slower diffusion of proton acceptors, leading to local acidification and dissolution of NiFe LDH structure. Conversely, highly alkaline environments provide more stable conditions for OER by ensuring efficient proton neutralization and preventing local acid formation [110]. However, increased pH also accelerates nucleophilic substitution of ammonium groups in AEMs, thereby deteriorating membrane stability [105]. Additionally, the deposition of carbonates when using K₂CO₃ electrolyte in AEMWE can further exacerbate degradation issues.

Scaled AEMWE devices may also experience increased degradation. Larger devices often operate with higher current densities and extended durations, accelerating degradation mechanisms such as membrane fouling, electrode corrosion, and gas management issues. Scaling up can introduce challenges related to uniformity of operating conditions, mass transport limitations, and mechanical stresses, all contributing to accelerated degradation compared to smaller-scale devices.

Therefore, in developing efficient and durable large-scale AEMWE electrolyzers, it is imperative to thoroughly evaluate the performance of various materials, particularly catalysts and membranes, under actual operating conditions and consider the impact of environmental factors on their stability.

6.2 Rationally designing materials

For stable and large-scale AEMWE applications, selecting appropriate materials is crucial for ensuring long-term performance and durability. Ni-Fe-Co-based catalysts have emerged as highly promising options for the OER due to their high mass activity and low OER onset potential. Current research on these catalysts primarily focuses on nanoscale features, core-shell structures, and high-surface-area layered configurations, such as NiFeO_xH_y and NiCoFeO_xH_y. Studies have demonstrated that Ni-Fe-Co-based materials can outperform traditional Ir-based or Ru-based OER catalysts in single-cell tests for AEMWE [111]. Further evaluation of the durability and elucidation of the failure mechanisms of Ni-Fe-Co-based catalysts under

both laboratory-scale and actual operating conditions are essential for advancing their practical applications [30]. Pt/C remains the most suitable HER catalyst for AEMWE due to its high activity and durability. However, researchers are eagerly seeking alternative, platinum-group-metal-free HER electrocatalysts for large-scale applications. Recent developments have focused on Ni-based, Co-based, and Fe-based catalysts for HER in AEMWE devices [25]. The durability of these materials in actual working environments should receive increased attention, akin to that given to OER catalysts.

Appropriate ionomers are crucial for enhancing the performance and stability of AEMWE, as catalyst detachment under high current densities is a major degradation mechanism [112]. DuPont's Nafion, which is widely used in PEMWE for its excellent chemical, thermal, and mechanical stability, can also be employed in AEMWE. Common anion exchange ionomers, such as Aquivion[®], Sustainion XB-7, and Aemion+[™], typically feature a hydrocarbon-based backbone and positively charged quaternary ammonium ion exchange groups [113]. Addressing the durability of ionomer materials under alkaline and oxidative potentials is vital for the long-term stability of AEMWE. Strategies to improve mechanical strength and enhance stability against alkaline and oxidative conditions include modifying molecular structures, tailoring functional group types and distributions, introducing cross-linking, and incorporating nanofillers or additives [114].

Research of GDL primarily focuses on engineering electrode architectures with controlled pore sizes, porosity, and surface areas to maximize reactant and product mass transport, improve catalyst utilization, and minimize ohmic losses. Integrating catalytic materials into porous electrode layers to enhance the efficiency of electrochemical reactions in AEMWE is also a productive approach. Research efforts should include scaling up GDL designs for practical implementation in larger-scale AEMWE devices, involving optimized manufacturing processes, electrode assembly techniques, and device integration strategies.

The interaction between different components must be carefully considered. For example, reactions between component materials can occur. Nuclear magnetic resonance spectroscopy revealed that the phenyl group of the ionomer gradually oxidized to benzoquinone on the catalyst layer surface over time during OER. Compared to perovskite oxide $\text{La}_{0.85}\text{Sr}_{0.15}\text{CoO}_3$, Pt/C and IrO_2 catalysts interact more strongly with the phenyl group, resulting in more severe oxidation phenomena [76].

6.3 Standardizing the assessment protocols

Evaluating the long-term stability of materials and devices for AEMWE typically requires extended periods of testing, often exceeding one year. This extended duration is necessary to accurately simulate real-world operating conditions and assess the durability, reliability, and performance degradation mechanisms over time [115]. Industrial environments pose additional challenges due to higher temperatures, greater mechanical stresses, and prolonged operational periods.

During long-term stability assessments, researchers monitor various parameters, including cell voltage, current density, gas crossover rates, membrane integrity, catalyst activity, and electrode morphology. These measurements offer insights into the degradation mechanisms affecting the AEMWE device and help identify strategies to enhance long-term performance and durability. Advanced characterization techniques, such as electrochemical methods, electron microscopy, X-ray diffraction, Raman spectroscopy, ultraviolet-visible spectroscopy, Fourier-transform infrared spectroscopy, and surface analysis, provide valuable information on catalyst structure-property relationships and degradation mechanisms at microstructural and electronic levels. Both ex-situ and in-situ microscopic and spectroscopic characterizations are extensively employed in electrocatalysis research [116–119]. For example, XPS and in-situ Raman spectroscopy revealed that during the HER of $\alpha\text{-Co(OH)}_2$ in 1 M KOH electrolyte, Co^{2+} was reduced to metallic Co and combined with OH^- to form soluble Co(OH)_3^- . When 0.1 M MoO_4^{2-} was added to 1 M KOH electrolyte, $\alpha\text{-Co(OH)}_2$ was protected because of the electrostatic repulsion, effectively inhibiting the corrosion of OH^- on $\alpha\text{-Co(OH)}_2$ [120].

However, characterizing devices under actual operating conditions to obtain comprehensive and relevant data remains challenging, as the working environment of a real electrochemical device can differ significantly from that of an in-situ testing system. Electrochemical techniques combined with ICP-MS allow for direct and in-situ measurements of elemental dissolution rates, providing insights into element-specific reaction mechanisms under operational conditions by coupling electrochemical flow cells with mass spectrometry. Online ICP-MS measurements of CuCoO_x OER catalyst showed significant dissolution of Cu and Co at open circuit potential (OCP) in neutral pH, indicating dealloying and surface instability. In contrast, alkaline conditions exhibited more stable behavior with reduced dissolution rates [44]. Additionally, electrolysis optical coherence tomography platform, which visualizes the dynamic electrochemical reaction process in real-time with high resolution (1–3 μm) and high frame rates (32 fps) using

polarized near-infrared light, can be a powerful tool for revealing the dynamics of electrochemistry and the transport of gaseous and liquid reactants in operating electrolyzers [121].

As electrolyzer size expands to the scale of square meters and the number of layers increases, voltage, current, reactants, products, and energy distributions on the interfaces are likely to become uneven. Moreover, the coupling and crosstalk of multiple dynamically interacting interfaces and bulk processes add complexity. Therefore, electrochemical techniques, as the most implementable characterization methods under working conditions, warrant further attention and development [122]. For example, EIS is a versatile and highly sensitive tool for measuring internal resistance. It enables in-situ monitoring of both external operating conditions and internal components, making it essential for electrolyzer development. EIS studies on PEMWE have identified degradation-affected components, indicating that the anode contributes more significantly to degradation than the cathode and suggesting possible polymer restructuring during operation, potentially due to membrane thinning [123].

To accelerate the evaluation process without compromising result reliability, researchers often use accelerated aging techniques such as accelerated stress testing or accelerated life testing. These methods expose the AEMWE device to accelerated degradation conditions, such as higher temperatures, dynamic potentials/current densities, or elevated pH levels, to simulate long-term operation in a shorter period. Although accelerated testing can provide valuable insights into material and device behavior over time, it is crucial to validate these results against real-world performance data to ensure their reliability and relevance. Ongoing research aims to refine testing methodologies and develop predictive models to improve the accuracy and efficiency of long-term stability assessments in AEMWE and other electrochemical devices.

In summary, AEMWE, as a next-generation technology for green hydrogen production, is poised to play a significant role in achieving sustainable development goals. Despite its potential, the inferior stability of AEMWE remains a critical bottleneck to practical applications. Addressing and mitigating the heterogeneous degradation mechanisms of AEMWE is crucial for advancing this technology. Continued research focused on improving material properties, enhancing membrane resilience, and understanding degradation processes is essential for realizing the full potential of AEMWE in sustainable hydrogen production.

Abbreviations

AEMWE Anion exchange membrane water electrolysis

AWE	Alkaline water electrolysis
PEMWE	Proton exchange membrane water electrolysis
AEM	Anion exchange membrane
OER	Oxygen evolution reaction
HER	Hydrogen evolution reaction
GDL	Gas diffusion layer
ICP-MS	Inductively coupled plasma mass spectrometer
CA	Chronoamperometry
RHE	Reversible hydrogen electrode
XPS	X-ray photoelectron spectroscopy
EDS	Energy dispersive X-ray spectroscopy
CV	Cyclic voltammetry
TEM	Transmission electron microscopy
LSV	Linear sweep voltammetry
DFT	Density functional theory
MEA	Membrane electrode assembly
CP	Chronopotentiometry
SEM	Scanning electron microscope

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Authors' contributions

JL and ZW organized the outline of the manuscript, drafted, and revised the manuscript. JL and RD conducted the cost analysis. YZ, MJ, HF, SW, CF, XY, QF, MUF, HK, AKA, and FL commented on the previous versions of the manuscript and revised the manuscript. JW conceptualized the manuscript and revised the manuscript. We ensure that all authors are included in the author list and its order has been agreed by all authors. All authors read and approved the final manuscript.

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Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated during the current study.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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