Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2026, Volume 17, Issue 4, Page 693-711

http://www.jmaterenvironsci.com

Corrosion-Resistant Multimetallic Ru-Based Catalysts for Enhanced Seawater Oxidation

Husaini M.
Department of Chemistry, College of Natural and Applied Sciences, Al-Qalam University Katsina, P.M.B. 2137, Nigeria

**Corresponding author, Email address: musahusaini36@gmail.com*

Received *05 Mar 2026,*
Revised *27 Apr 2026,*
Accepted *30 Apr 2026*

Keywords:
- ✓ *Seawater electrolysis;*
- ✓ *Multimetallic Ru catalysts;*
- ✓ *Oxygen evolution reaction;*
- ✓ *AEM electrolyzers;*
- ✓ *Corrosion resistance; Catalyst stability;*
- ✓ *Nanostructuring*

Citation*: Husaini M. (2026). Corrosion-Resistant Multimetallic Ru-Based Catalysts for Enhanced Seawater Oxidation, J. Mater. Environ. Sci., 17(4), 693-711.*

Abstract: The growing global demand for clean and sustainable energy has intensified research into hydrogen production from seawater electrolysis, offering a renewable pathway with minimal environmental impact. Multimetallic Ru-based catalysts have emerged as a leading solution, demonstrating superior activity, stability, and corrosion resistance compared to single-metal systems, especially under chloride-rich conditions. This review examines the design principles, including electronic structure modulation, surface reconstruction, and protective layer formation, as well as advanced strategies such as nanostructuring, defect engineering, hybrid systems, and single-atom catalysts. The integration of these catalysts into anion exchange membrane (AEM) electrolyzers is evaluated, highlighting critical factors such as catalyst–membrane compatibility, mass transport efficiency, and scale-up potential. Comparative analysis underscores the enhanced performance of Ru–Mo–Ni multimetallic systems over RuO_2 and Ni-based alternatives, with lower overpotentials, improved long-term durability, and higher selectivity for oxygen evolution. The review also emphasizes cost considerations and practical feasibility for industrial hydrogen generation. Collectively, these insights provide a roadmap for the rational design of high-performance, durable, and scalable electrocatalysts for sustainable hydrogen production from seawater.

1. Introduction

The increasing demand for clean and sustainable energy has accelerated global interest in hydrogen as a promising energy carrier. Among the various production routes, water electrolysis stands out due to its potential for generating high-purity hydrogen with minimal environmental impact, particularly when powered by renewable energy sources (Zhang *et al.*, 2024; Tsacheva *et al.*, 2025; Husaini, 2026). However, the reliance on freshwater resources presents a significant limitation, motivating the exploration of alternative water sources such as seawater, which constitutes approximately 96.5% of the Earth's total water reserves (Cui *et al.*, 2024). In addition, the integration of renewable electricity with electrolysis systems offers a pathway toward decarbonizing industrial sectors and achieving long-term energy security (Tripathi and Sinha, 2024; Baek *et al.*, 2025). As global energy consumption continues to rise, the need for scalable and resource-efficient hydrogen production technologies becomes increasingly critical (Lyu and Serov, 2023).

Despite its abundance, the direct use of seawater in electrolysis systems introduces substantial technical challenges. One of the primary issues is the high concentration of chloride ions (Cl^-), which can aggressively attack catalyst surfaces, leading to corrosion, structural degradation, and reduced operational lifespan (Dafali *et al.*, 2002; El Issami *et al.*, 2007; Ke *et al.*, 2021; Wang *et al.*, 2024). In addition, chloride ions promote the chlorine evolution reaction (CER), a competing electrochemical process that diminishes the efficiency and selectivity of the oxygen evolution reaction (OER), which is essential for effective water splitting (Li *et al.,* 2024). The presence of other dissolved species in seawater, such as magnesium, calcium, and sulfate ions, further complicates the electrochemical environment by contributing to scaling, precipitation, and electrode fouling (Zhang *et al.,* 2025). These factors collectively hinder the stability and efficiency of electrolysis systems operating under real seawater conditions (Zhao *et al.,* 2026; Sun *et al.,* 2023).

Ruthenium (Ru)-based catalysts have attracted considerable attention due to their excellent intrinsic activity toward OER, characterized by low overpotentials and favorable reaction kinetics (Yu *et al.,* 2023; Kang *et al.,* 2023). These properties make Ru one of the most efficient noble metals for anodic reactions in electrolysis systems. Furthermore, Ru-based materials exhibit fast electron transfer kinetics and favorable adsorption energies for key reaction intermediates, making them highly suitable for high-performance catalytic applications (Cui *et al.,* 2024; Tripathi and Sinha, 2024). However, the practical application of Ru-based catalysts in seawater environments is hindered by their limited stability, as they are prone to dissolution and deactivation under harsh saline conditions (Wang *et al.,* 2024; Zhang *et al.,* 2025). This instability is often associated with the oxidation of active Ru species and the breakdown of catalyst structures during prolonged electrochemical operation (Zhao *et al.,* 2026; Sun *et al.,* 2023).

To address these limitations, recent research has focused on multimetallic Ru-based catalysts, where Ru is combined with other transition metals to enhance durability, reduce cost, and improve performance through synergistic effects (Kang *et al.,* 2023; Salaev *et al.,* 2026). Secondary metals such as nickel, molybdenum, iron, and cobalt can modify the electronic structure of Ru, promote stable surface phases, and form protective layers against chloride-induced corrosion (Cui *et al.,* 2024; Baek *et al.,* 2025; Li *et al.,* 2024). Structural engineering approaches like nanostructuring increase accessible active sites and improve mass transport, further enhancing catalytic activity and stability (Zhang *et al.,* 2025; Husaini *et al.,* 2025; Zhao *et al.,* 2026; Husaini, 2024). This review aims to critically evaluate corrosion-resistant multimetallic Ru-based catalysts for seawater oxidation, highlight design strategies and performance improvements, and identify future research directions for efficient and durable seawater electrolysis (Tripathi and Sinha, 2024; Lyu and Serov, 2023).

2. Fundamentals of Seawater Oxidation

2.1 Oxygen Evolution Reaction (OER)

The oxygen evolution reaction (OER) is the primary anodic process in water electrolysis, responsible for generating oxygen gas while simultaneously supplying electrons for the hydrogen evolution reaction at the cathode (Li *et al.,* 2023; Ren *et al.,* 2023). In alkaline media, OER involves the oxidation of hydroxide ions (OH^-) and can be expressed as:

$$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$$

OER is a complex multi-electron transfer process and generally exhibits slow reaction kinetics, which necessitates the use of efficient electrocatalysts (Sun *et al.,* 2023; Deng *et al.,* 2023). One of the most important parameters used to evaluate OER performance is the overpotential, defined as the additional voltage required beyond the theoretical value to drive the reaction. Lower overpotential indicates better catalytic efficiency and reduced energy loss. Another key parameter is the Tafel slope, which provides insight into the reaction mechanism and the rate-determining step. A smaller Tafel slope suggests faster reaction kinetics and improved catalytic activity.

In addition, OER performance is strongly influenced by factors such as catalyst surface area, density of active sites, electronic structure, and the adsorption behavior of key intermediates such as OH*, O*, and OOH* (Zhang *et al.,* 2024; He *et al.,* 2023). Optimizing these parameters enhances the reaction pathway and improves oxygen production efficiency, especially under the complex conditions associated with seawater electrolysis (Zhou *et al.,* 2023).

2.2 Competing Chlorine Evolution Reaction (CER)

In seawater electrolysis, the high concentration of chloride ions (Cl^-, approximately 0.5 M) leads to the occurrence of a competing anodic reaction known as the chlorine evolution reaction (CER) (Wu *et al.,* 2024; Qiu *et al.,* 2024). This reaction proceeds as:

$2Cl^- \rightarrow Cl_2 + 2e^-$

The CER results in the formation of chlorine gas (Cl_2), which is highly toxic and corrosive. Its generation not only raises safety concerns but also accelerates the degradation of electrode materials and catalysts (Huang *et al.,* 2024). Furthermore, CER competes directly with OER for active sites on the catalyst surface, thereby reducing the selectivity and Faradaic efficiency toward oxygen production (Liang *et al.,* 2023).

Chloride ions tend to adsorb strongly onto catalyst surfaces, interfering with the adsorption of hydroxide ions and inhibiting the formation of OER intermediates (Feng *et al.,* 2024). This competitive adsorption increases energy barriers for OER while favoring undesired side reactions. In addition, the presence of chloride ions promotes corrosion, structural instability, and gradual deactivation of the catalyst (Liu *et al.,* 2025). As a result, both the efficiency and durability of seawater electrolysis systems are significantly compromised (Chen *et al.,* 2024).

Therefore, developing catalysts that can selectively promote OER while suppressing CER and resisting chloride-induced corrosion is essential for achieving stable and efficient seawater oxidation (Gao *et al.,* 2023).

3. Challenges in Seawater Electrolysis

3.1 Chloride-Induced Corrosion

One of the most significant challenges in seawater electrolysis is corrosion caused by the high concentration of chloride ions (Cl^-). These ions are highly aggressive and can interact with catalyst surfaces, leading to gradual dissolution of active materials, particularly for metal-based electrocatalysts. This dissolution reduces the amount of available catalytic material and negatively affects overall performance (Wang *et al.,* 2023; Li *et al.,* 2023).

In addition, chloride ions can cause surface poisoning by adsorbing strongly onto active sites, thereby blocking the adsorption of hydroxide ions and inhibiting the oxygen evolution reaction. This competitive adsorption reduces catalytic efficiency and promotes undesirable side reactions (Gao *et al.,* 2023). Furthermore, prolonged exposure to chloride-rich environments results in structural degradation of the catalyst, including lattice distortion, formation of defects, and eventual breakdown of the material (Zhang *et al.,* 2023; Zhao *et al.,* 2024). These effects collectively limit the durability and reliability of electrocatalysts in seawater systems (Chen *et al.,* 2023).

Related corrosion reaction
$\text{Metal} \rightarrow \text{Metal}^{n+} + ne^-$

3.2 Catalyst Instability

Catalyst instability remains a critical issue, particularly for noble metal-based systems such as ruthenium (Ru). Under anodic conditions, Ru leaching can occur, where active Ru species dissolve into the electrolyte, leading to a gradual decline in catalytic activity (Xu *et al.,* 2024). This process is often accelerated in the presence of chloride ions and high operating potentials.

Another challenge involves changes in surface oxidation states during operation. Continuous electrochemical cycling can alter the oxidation state of the catalyst, affecting its electronic structure and catalytic behavior (Sun *et al.,* 2023). These transformations may lead to less active or unstable surface phases. As a result, there is a progressive loss of active sites, which directly reduces the efficiency of the oxygen evolution reaction (Yang *et al.,* 2024). Maintaining structural and chemical stability of catalysts under harsh seawater conditions is therefore essential for long-term operation (Liu *et al.,* 2025).

3.3 Industrial Limitations

Despite significant laboratory-scale advancements, several challenges hinder the large-scale implementation of seawater electrolysis. One major limitation is the difficulty in achieving and sustaining high current densities, typically above 500 mA cm^{-2}, which are required for industrial hydrogen production (He *et al.,* 2025). At such high current densities, issues such as increased overpotential, mass transport limitations, and accelerated catalyst degradation become more pronounced (Tang *et al.,* 2024).

Another critical concern is long-term operational stability. Many reported systems exhibit stable performance only for relatively short durations, and maintaining consistent activity beyond 200 hours remains challenging (Zhou *et al.,* 2024). Degradation mechanisms, including corrosion, fouling, and catalyst deactivation, contribute to this limitation (Park *et al.,* 2023). These factors highlight the need for the development of robust, corrosion-resistant, and highly efficient catalyst systems capable of operating under industrially relevant conditions.

Relevant electrochemical relation (current density):

$$j = \frac{I}{A} \tag{Eqn. 1}$$

Where:

j = current density (mA cm^{-2})

I = current (mA)

A = electrode area (cm^2)

4. Multimetallic Ru-Based Catalysts

4.1 Design Concept

The development of multimetallic ruthenium (Ru)-based catalysts has emerged as an effective strategy to overcome the limitations associated with single-metal systems in seawater electrolysis (Li *et al.,* 2023; Kumar *et al.,* 2023). In this approach, Ru is combined with other transition metals such as nickel (Ni), molybdenum (Mo), iron (Fe), and cobalt (Co) to create hybrid catalytic systems with improved functionality.

The primary objective of this design is to enhance catalyst stability, particularly under chloride-rich and highly oxidative conditions (He *et al.,* 2025). Incorporating secondary metals helps to suppress corrosion and reduce the dissolution of Ru species during operation. Another important goal is to minimize the usage of Ru, which is a scarce and expensive noble metal, thereby lowering overall material costs without compromising performance (Zhao *et al.,* 2024).

In addition, multimetallic systems are engineered to improve catalytic activity by tuning the electronic structure and optimizing the adsorption energies of reaction intermediates involved in the oxygen evolution reaction (OER) (Yang *et al.,* 2023). The interaction between different metal components can create synergistic effects that enhance charge transfer, increase the number of active sites, and improve overall reaction kinetics (Sun *et al.,* 2024).

4.2 Types of Multimetallic Systems

(a) Ru–Mo-Based Catalysts

Ruthenium–molybdenum (Ru–Mo) catalysts are widely studied due to their enhanced resistance to chloride-induced corrosion (Zhang *et al.,* 2023). Molybdenum plays a crucial role by forming stable oxide species under anodic conditions, which act as a protective barrier on the catalyst surface. In alkaline or neutral environments, molybdenum can be oxidized to form molybdate ions:

$$Mo + 4OH^- \rightarrow MoO_4^{2-} + 2H_2O + 2e^-$$

The generated MoO_4^{2-} species contribute to the formation of a negatively charged surface layer that repels chloride ions (Cl^-), thereby reducing their adsorption and minimizing corrosion (Tang *et al.,* 2024). This protective effect enhances catalyst durability while maintaining catalytic activity for OER.

(b) Ru–Ni-Based Catalysts

Ruthenium–nickel (Ru–Ni) systems are known for their improved electrical conductivity and catalytic performance (Park *et al.,* 2024). Nickel serves as a conductive matrix that facilitates electron transfer during electrochemical reactions. Under anodic conditions, nickel can undergo oxidation to form nickel oxyhydroxide (NiOOH), which is an active phase for OER:

$$Ni(OH)_2 + OH^- \rightarrow NiOOH + H_2O + e^-$$

The presence of NiOOH enhances the adsorption and transformation of OER intermediates, thereby improving reaction kinetics (Chen *et al.,* 2023). Furthermore, the interaction between Ru and Ni can modify the electronic environment of active sites, leading to increased catalytic efficiency and better utilization of Ru (Wu *et al.,* 2023).

(c) Ru–Mo–Ni (Trimetallic Systems)

Trimetallic systems consisting of Ru, Mo, and Ni combine the advantages of each individual component to achieve superior performance (Liu *et al.,* 2025). In these systems, Ru primarily provides highly active sites for the oxygen evolution reaction, while Mo contributes to corrosion resistance through the formation of protective oxide layers. Nickel, on the other hand, offers structural stability and enhanced electrical conductivity.

The synergistic interaction among these elements leads to the formation of stable composite phases such as nickel molybdate:

$$Ni^{2+} + MoO_4^{2-} \rightarrow NiMoO_4$$

The formation of $NiMoO_4$ and related molybdate species creates a protective and stable surface environment that limits chloride ion attack and reduces catalyst degradation (Lin *et al.,* 2024). At the same time, the conductive Ni framework supports efficient electron transport, while Ru ensures high catalytic activity.

Overall, the integration of these three components results in a well-balanced system with improved activity, stability, and corrosion resistance, making trimetallic Ru-based catalysts highly promising for practical seawater electrolysis applications (Chen *et al.,* 2025).

5. Mechanisms of Corrosion Resistance

5.1 Electronic Structure Modulation

One of the primary strategies for improving the corrosion resistance and catalytic performance of Ru-based electrocatalysts is the modulation of their electronic structure. Incorporating secondary transition metals, such as Ni, Mo, or Co, shifts the d-band center of Ru. This adjustment directly influences the adsorption energies of critical intermediates involved in the oxygen evolution reaction (OER), such as hydroxyl (*OH), oxygen (*O), and hydroperoxyl (OOH). By optimizing these interactions, the catalyst surface can maintain efficient reaction kinetics while preventing excessive binding that could lead to surface blockage or catalyst degradation (Li *et al.,* 2025; Zhang *et al.,* 2025).

The stepwise OER mechanism in alkaline conditions is as follows:

1. $OH^- + * \rightarrow OH^* + e^-$
2. $OH^* + OH^- \rightarrow O^* + H_2O + e^-$
3. $O^* + OH^- \rightarrow OOH^* + e^-$
4. $OOH^* + OH^- \rightarrow O_2 + H_2O + e^-$

Here, the asterisk (*) represents an active site on the catalyst surface. By carefully tuning the electronic structure, the adsorption energies of these intermediates are balanced, reducing the likelihood of surface poisoning and enhancing both the catalytic activity and long-term stability of the catalyst under harsh seawater conditions (He *et al.,* 2025).

5.2 Surface Reconstruction

During electrochemical operation, Ru-based catalysts and their multimetallic derivatives undergo dynamic surface reconstruction, which is a crucial factor in maintaining high catalytic performance. This restructuring involves the transformation of the original metal surface into highly active oxide or oxyhydroxide phases that are more effective for OER. For Ru-based catalysts, surface oxidation typically leads to the formation of ruthenium dioxide (RuO_2), which exhibits high catalytic activity. In nickel-containing systems, the formation of nickel oxyhydroxide (NiOOH) under anodic conditions provides additional active sites and improves charge transfer during water oxidation (Moyo *et al.,* 2025).

The relevant electrochemical reactions for surface reconstruction include:

$Ru \rightarrow RuO_2 + 4H^+ + 4e^-$
$Ni(OH)_2 + OH^- \rightarrow NiOOH + H_2O + e^-$

These reconstructed phases continuously expose new active sites, enhance electron mobility, and improve catalytic performance. Additionally, dynamic surface reconstruction helps mitigate catalyst degradation by maintaining a stable surface composition and structure even in chloride-rich seawater, thus prolonging the operational lifetime (Wang *et al.,* 2026).

5.3 Protective Layer Formation

The formation of protective layers is another essential mechanism to resist corrosion and maintain catalyst durability. In multimetallic Ru-based systems, molybdenum can be oxidized under operating conditions to generate molybdate species (MoO_4^{2-}). These negatively charged layers effectively repel chloride ions (Cl^-), limiting their adsorption on the catalyst surface and reducing corrosion rates (Xin *et al.,* 2024):

$$Mo + 4OH^- \rightarrow MoO_4^{2-} + 2H_2O + 2e^-$$

Carbon coatings on the catalyst can act as a physical barrier, preventing direct exposure to the electrolyte while allowing efficient electron transport. Similarly, oxide shells formed during electrochemical cycling, such as RuO_2 or NiOOH, create an additional protective layer that prevents metal dissolution:

$$M \rightarrow MOx + xH^+ + xe^-$$

The combination of these strategies chemical protection from molybdate species and physical protection from carbon and oxide layers creates a dual defense mechanism. This synergy significantly enhances long-term catalyst stability, with some engineered systems demonstrating stable operation for over 2000 hours under highly corrosive seawater electrolysis conditions (Liu *et al.,* 2025; He *et al.,* 2025). Protective layer formation is therefore a key determinant for designing durable and high-performance multimetallic Ru-based electrocatalysts.

6. Synthesis Strategies for Multimetallic Ru-Based Catalysts

6.1 Hydrothermal Synthesis

Hydrothermal synthesis is a versatile and widely used method for preparing multimetallic Ru-based catalysts due to its ability to produce highly uniform nanostructures with controlled size, morphology, and crystallinity under high-temperature and high-pressure aqueous conditions. In this method, metal precursors, such as $RuCl_3$, $Ni(NO_3)_2$, and MoO_3, are dissolved in water or mixed solvents. The solution is sealed in an autoclave and heated, which promotes nucleation and growth of the catalyst particles. By carefully adjusting parameters such as temperature, reaction time, and precursor concentration, it is possible to control the crystal phase, particle size distribution, and porosity of the final product, all of which are critical for optimizing catalytic performance (Lin *et al.,* 2024).

A representative reaction for the hydrothermal formation of a Ru–Ni–Mo oxide catalyst can be expressed as:

$$RuCl_3 + Ni(NO_3)_2 + MoO_3 + H_2O \rightarrow RuNiMoO_x + \text{by-products}$$

Hydrothermally synthesized catalysts often exhibit high surface areas, well-dispersed active sites, and hierarchical structures, which enhance the mass transport of reactants and improve overall oxygen evolution reaction (OER) activity in seawater electrolysis (Zhang *et al.,* 2025).

6.2 Electrodeposition

Electrodeposition is a controllable and scalable method that allows the direct growth of multimetallic catalysts onto conductive substrates, such as nickel foam, carbon paper, or titanium mesh. By adjusting the applied potential, current density, electrolyte composition, and deposition time, researchers can finely tune the composition, thickness, morphology, and surface roughness of the deposited catalyst layer. This technique also promotes strong adhesion of the active material to the substrate, which improves mechanical and electrochemical stability under harsh seawater conditions (Yu *et al.,* 2024). A simplified electrodeposition reaction for a Ru–Ni–Mo system can be written as:

$Ru^{3+} + Ni^{2+} + Mo^{6+} + 8e^{-} \rightarrow RuNiMo$ (metal/alloy deposit)

Electrodeposition allows the formation of uniform multimetallic alloys or mixed oxides with well-dispersed active sites, which enhances charge transfer efficiency and catalytic durability (Park *et al.,* 2024).

6.3 Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) is employed to deposit thin films or nanostructured coatings with precise composition and uniformity. In this process, volatile metal precursors are transported in a carrier gas and react on a heated substrate to form a solid layer. CVD enables the integration of multiple metals in a single step, ensuring homogeneous distribution of active sites and precise control over the catalyst structure. This is particularly important for Ru-based multimetallic systems where uniformity and surface exposure significantly affect OER activity (Chen *et al.,* 2024).

A general CVD reaction for Ru–Mo–Ni deposition is:

$Ru(CO)_3 + Ni(CO)_4 + Mo(CO)_6 \rightarrow RuNiMo$ (thin film) + CO (gas)

CVD-derived catalysts typically exhibit high crystallinity, controlled surface facets, and robust intermetallic interactions, all of which contribute to enhanced electron transport, better reaction kinetics, and improved corrosion resistance during seawater electrolysis (Qin and Zhou, 2025).

6.4 Thermal Annealing

Thermal annealing is a widely applied post-synthesis treatment that enhances crystallinity, promotes alloy formation, and improves metal–metal interactions in multimetallic catalysts. By heating the material under inert, reducing, or controlled atmospheres, residual precursors are removed, and the lattice structure can reorganize to form highly active phases with optimized electronic properties. This treatment also helps stabilize the catalyst against dissolution and degradation under harsh electrochemical conditions (Xu *et al.,* 2025). For example, thermal annealing of a hydrothermally synthesized Ru–Ni–Mo precursor can be represented as:

$RuNiMoO_x$ + heat $\rightarrow$ RuNiMo alloy + O_2

This process improves conductivity, reinforces structural integrity, and maximizes exposure of active sites, which is crucial for achieving high current densities and long-term operational stability in seawater electrolysis (He *et al.,* 2023).

6.5 Key Considerations in Catalyst Design

Designing high-performance multimetallic Ru-based catalysts requires careful consideration of particle size, metal dispersion, and structural porosity. Smaller particles increase surface-to-volume ratios, exposing more catalytic sites. Uniform distribution of Ru and secondary metals ensures consistent electronic and catalytic properties across the surface. Porous nanostructures facilitate efficient mass transport of reactants and products, reduce diffusion limitations, and help prevent local concentration gradients. Additionally, controlling defects and creating hierarchical structures can further improve both catalytic activity and durability. By integrating these strategies with hydrothermal, electrodeposition, CVD, and thermal annealing methods, researchers can produce highly active, robust, and corrosion-resistant catalysts suitable for industrial seawater electrolysis applications (Sun *et al.,* 2025; Shen *et al.,* 2026; Gao *et al.,* 2025).

7. Performance Evaluation of Multimetallic Ru-Based Catalysts

7.1 Activity Metrics

The catalytic activity of multimetallic Ru-based systems is typically evaluated using key electrochemical parameters. Overpotential, measured at benchmark current densities such as 10, 100, or 500 mA cm^{-2}, indicates the extra energy required beyond the thermodynamic potential to drive water splitting. Lower overpotentials reflect efficient catalysts with favorable kinetics (Guo *et al.,* 2026). Another crucial metric is the Tafel slope, which provides insight into the rate-determining step and electron transfer kinetics, while high current density correlates directly with higher hydrogen production rates in seawater electrolysis (Xin *et al.,* 2025).

The Tafel equation,

$\eta = a + b \log(j)$, relates the overpotential η to the current density j, where b is the Tafel slope. Catalysts exhibiting low overpotential and low Tafel slope at high current densities indicate superior intrinsic activity and improved mass transport characteristics within the catalytic layer (Ran *et al.,* 2025).

7.2 Stability Metrics

Long-term stability is a critical performance metric for multimetallic Ru-based catalysts, particularly under chloride-rich seawater conditions. Chloride ions can induce corrosion, leading to metal dissolution and progressive loss of active sites. The relevant anodic dissolution reactions include:

$Ru \rightarrow Ru^{n+} + ne^{-}$
$Ni \rightarrow Ni^{2+} + 2e^{-}$

Stability tests are conducted over extended durations (tens to thousands of hours) to monitor performance degradation, structural changes, and sustained activity (Qin and Zhou, 2025). Post-operational analysis such as XRD, TEM, and surface spectroscopy is used to confirm that catalysts retain their composition, crystallinity, and morphology. Improved corrosion resistance and minimal loss of active surface area over time are key indicators of catalyst robustness in practical seawater electrolysis designs (Sun *et al.,* 2025).

7.3 Selectivity

Selectivity defines how efficiently the catalyst directs the electrochemical reaction toward the desired oxygen evolution reaction (OER) rather than the competing chlorine evolution reaction (CER), which is thermodynamically favored in chloride-containing electrolytes. The reactions for OER and CER are:

OER: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$
CER: $2Cl^- \rightarrow Cl_2 + 2e^-$

High selectivity toward OER is quantified by the Faradaic efficiency (FE), which measures the fraction of the applied current contributing to oxygen evolution:

$$\text{FE } (\%) = \frac{\text{moles of } O_2 \text{ produced} \times 4F}{\text{total charge}} \times 100 \qquad \textbf{Eqn. 2}$$

where F is the Faraday constant. Analytical techniques such as in-situ gas chromatography or electrochemical mass spectrometry are used to measure O_2 and Cl_2 generation, ensuring accurate evaluation of OER vs CER efficiency. Achieving high selectivity with minimal CER is crucial for the development of efficient, durable catalysts capable of operating in real seawater while maximizing hydrogen output (Li *et al.,* 2024; Baek *et al.,* 2025).

8. Advanced Design Strategies

8.1 Nanostructuring

Nanostructuring is a fundamental approach to improving both the activity and stability of Ru-based electrocatalysts. High-aspect-ratio morphologies such as nanorods, nanosheets, and nanoflowers significantly increase the surface-to-volume ratio, which exposes a greater number of active sites for the oxygen evolution reaction (Xu *et al.,* 2023). These nanostructures also enhance mass transport by reducing diffusion limitations for reactants and products, particularly at high current densities (Li *et al.,* 2023). Additionally, the uniform dispersion of multimetallic components on nanostructured surfaces maximizes synergistic interactions between Ru and secondary metals, while shorter electron pathways accelerate charge transfer, improving overall reaction kinetics. Nanostructures further contribute to mechanical stability by resisting catalyst agglomeration and maintaining consistent exposure of active sites, which is particularly beneficial for prolonged operation in chloride-rich seawater (Xu *et al.,* 2023). Possible surface adsorption reaction facilitated by nanostructures:

$OH^- \rightarrow {}^*OH + e^-$

8.2 Defect Engineering

Defect engineering involves creating controlled oxygen vacancies, cationic vacancies, or lattice distortions in Ru-based materials, which can drastically modulate the electronic structure (Wen *et al.,* 2023). These defects act as highly reactive sites for hydroxide ions and oxygen intermediates, enhancing adsorption/desorption kinetics and accelerating electron transport. Oxygen vacancies improve electron mobility, promote rapid surface reorganization under electrochemical stress, and provide dynamic stabilization of the catalyst surface in harsh chloride-rich environments (Zhang *et al.,* 2024). Controlled defect introduction also prevents over-binding of intermediates, which minimizes surface poisoning and balances activity, selectivity, and durability. By combining defect engineering with multimetallic synergy, catalysts can achieve sustained performance in challenging seawater electrolysis conditions (Wen *et al.,* 2023).

Representative defect-mediated reaction:

$M–\square + OH^- \rightarrow M–OH + e^-$

8.3 Hybrid Systems

Hybrid systems integrate Ru-based electrocatalysts with conductive or chemically active supports, such as carbon materials or metal oxides, to improve overall performance (Chen *et al.,* 2023). Carbon supports like graphene and carbon nanotubes provide high conductivity, structural reinforcement, and corrosion protection, while metal oxides such as NiO and Co_3O_4 enhance electron transfer and stabilize catalytic intermediates (Wu *et al.,* 2024). Hybridization also promotes uniform Ru dispersion, increasing the number of accessible active sites and reducing metal leaching, which is critical for long-term stability at high current densities. These systems efficiently manage local reaction environments, mitigating chloride-induced corrosion and sustaining catalytic activity over prolonged periods (Chen *et al.,* 2023). Electrochemical coupling reaction in hybrid systems:

$Ru–O–C + OH^- \rightarrow Ru–OOH + e^- + C$

8.4 Single-Atom Catalysts

Single-atom catalysts (SACs) represent the ultimate strategy for maximizing atomic efficiency by anchoring isolated Ru atoms on robust supports like metal oxides or nitrogen-doped carbon (Wang *et al.,* 2024). SACs allow precise tuning of the electronic environment of each active site, preventing metal aggregation and enhancing corrosion resistance (Li *et al.,* 2024). The strong metal-support interactions stabilize these single-atom sites even under aggressive chloride-rich seawater conditions, ensuring high catalytic efficiency, excellent oxygen evolution selectivity, and superior long-term durability. SACs also minimize precious metal loading while maintaining exceptional activity, which is vital for scaling up sustainable hydrogen production technologies (Wang *et al.,* 2024). Representative single-atom reaction:

$Ru_{sa} + H_2O \rightarrow Ru_{sa}–OH + H^+ + e^-$

9. Integration into Electrolyzer Systems

9.1 Focus: Anion Exchange Membrane (AEM) Electrolyzers

Anion exchange membrane (AEM) electrolyzers operate under alkaline conditions and have gained significant attention due to their lower cost compared to proton exchange membrane (PEM) systems (Godel *et al.,* 2026). The alkaline environment allows the use of non-precious metal catalysts, reducing overall system cost while maintaining high performance. Recent developments in membrane electrode assembly (MEA) design have improved ion conductivity and mechanical stability, which are critical for efficient water splitting in large-scale applications (Mishra *et al.,* 2026). Integration of advanced multimetallic Ru-based catalysts into AEM systems has shown promising activity and durability, ensuring sustainable hydrogen production (Vinodh *et al.,* 2023).

9.2 Catalyst–Membrane Compatibility

The compatibility between catalysts and membranes is essential for optimal electrolysis performance. Poor adhesion or chemical incompatibility can result in delamination, reduced ion transport, and accelerated degradation (Li *et al.,* 2024). Engineering the catalyst surface, including surface functionalization or hybrid support structures, enhances interaction with the polymeric membrane, minimizing interfacial resistance and improving overall cell efficiency (Li *et al.,* 2023). Compatibility considerations are particularly important when scaling up electrolyzers, as uniform catalyst distribution and stable membrane contact are critical for long-term operation (Rodríguez *et al.,* 2025).

9.3 Mass Transport Efficiency

Efficient mass transport of water, hydroxide ions, and oxygen is crucial to maintain high current densities in AEM electrolyzers. Optimization of the gas diffusion layer (GDL) and pore architecture improves reactant supply and product removal, reducing concentration polarization (Liu *et al.,* 2024). Additionally, three-dimensional porous electrodes and nanostructured catalysts enhance mass transport by shortening diffusion paths and exposing more active sites for electrochemical reactions (Park *et al.,* 2023). These structural innovations allow electrolyzers to operate efficiently at industrially relevant current densities without excessive voltage loss (Li *et al.,* 2023).

9.4 Scale-Up Potential

Scaling up AEM electrolyzers for industrial hydrogen production requires addressing both engineering and materials challenges. Recent studies demonstrate that robust, low-cost membranes, coupled with corrosion-resistant catalysts, can maintain stable performance over extended operation (Zhu *et al.,* 2024). Proper system integration, including flow-field design and thermal management, is essential to ensure uniform current distribution and prevent localized degradation (Falcão, 2023). With these advances, AEM electrolyzers are emerging as a viable alternative to PEM systems for sustainable, large-scale hydrogen generation (Li *et al.,* 2024).

10. Comparative Analysis

10.1 Activity

The catalytic activity of electrocatalysts is a crucial parameter in seawater electrolysis, as it determines the efficiency of hydrogen production and the overpotential required to drive the oxygen evolution reaction (OER). Ru–Mo–Ni multimetallic catalysts consistently outperform single-metal RuO_2 and Ni-based systems due to the synergistic combination of their components. Ruthenium provides highly active sites for OER, molybdenum contributes to enhanced electronic properties and surface stabilization, and nickel improves conductivity and facilitates charge transfer (Chen *et al.,* 2024). The multimetallic architecture also reduces the aggregation of Ru atoms, ensuring that a maximum number of active sites remain exposed. Ni-based catalysts, while cost-effective and moderately active, require higher applied potentials to achieve similar current densities and often exhibit slower reaction kinetics in chloride-rich electrolytes (Gao *et al.,* 2024). RuO_2 alone shows high initial activity but suffers from partial dissolution under long-term operation, particularly in the presence of Cl^- ions, which can hinder overall efficiency (Park *et al.,* 2023). These differences highlight the importance of multimetallic design for balancing high activity and long-term operational stability.

10.2 Stability

Long-term stability is a decisive factor for industrial applicability. Ru–Mo–Ni catalysts show exceptional stability due to the formation of protective MoO_4^{2-} layers and robust structural frameworks that resist chloride-induced corrosion (Wang *et al.,* 2023). These catalysts maintain high activity over extended periods, with minimal Ru leaching or structural deformation. In contrast, RuO_2, although initially active, gradually loses efficiency due to partial dissolution and surface restructuring under harsh saline conditions (Liu *et al.,* 2026). Ni-based catalysts generally exhibit moderate stability; their robustness can be enhanced through supportive oxide substrates, but they still underperform compared to multimetallic Ru systems in long-duration tests. The stability differences can be explained through electrochemical reactions illustrating metal dissolution and reformation:

$$M \rightarrow M^{n+} + ne^-$$

The superior durability of Ru–Mo–Ni catalysts ensures that industrial-scale electrolyzers can operate reliably without frequent replacement of catalytic components.

10.3 Cost

Economic considerations play a central role in selecting seawater electrocatalysts. Ni-based catalysts are highly cost-effective, leveraging earth-abundant elements and avoiding expensive noble metals (Singh *et al.,* 2025). RuO_2 and Ru–Mo–Ni catalysts incur higher material costs due to the inclusion of ruthenium, a scarce and expensive metal (Zheng *et al.,* 2024). However, the enhanced durability, reduced overpotential, and longer operational lifetime of Ru–Mo–Ni catalysts can offset the initial investment, making them economically viable for large-scale applications (Kumar *et al.,* 2026). When evaluating total cost of ownership, the reduction in downtime and maintenance requirements for multimetallic systems often outweighs the initial material expense, particularly in industrial hydrogen production scenarios.

10.4 Corrosion Resistance

Corrosion resistance is a critical determinant of long-term performance, especially in chloride-rich seawater environments. Ru–Mo–Ni catalysts outperform both single-metal RuO_2 and Ni-based systems, as Mo forms protective oxide layers that repel Cl^- ions, while Ni provides structural stabilization and enhanced electronic conductivity (Chen *et al.,* 2024; Wang *et al.,* 2023). Ni-based catalysts show moderate resistance but can suffer localized pitting or gradual surface degradation under extended operation (Gao *et al.,* 2024). RuO_2 is highly susceptible to chloride-induced dissolution, highlighting the limitations of single-metal systems in saline electrolytes (Park *et al.,* 2023). Typical corrosion reactions include:

$$M + Cl^- \rightarrow MCl^+ + e^-$$

Overall, the multimetallic design of Ru–Mo–Ni ensures a balance of activity, stability, and corrosion resistance, making it the preferred choice for industrial seawater electrolysis.

Conclusion

Multimetallic Ru-based catalysts represent a transformative approach to seawater electrolysis, addressing key challenges such as chloride-induced corrosion, catalyst degradation, and limited industrial scalability. Incorporating secondary metals like Mo, Ni, and Co provides synergistic benefits, including enhanced activity, structural stability, and corrosion resistance, while reducing overall Ru content and associated costs. Advanced design strategies, such as nanostructuring, defect engineering, hybridization with carbon or metal oxides, and single-atom configurations, further optimize active site exposure, electron transfer efficiency, and long-term durability. These catalysts demonstrate superior performance when integrated into AEM electrolyzers, offering improved mass transport, catalyst–membrane interaction, and scale-up potential. Comparative analyses reveal that Ru–Mo–Ni systems outperform single-metal RuO_2 and Ni-based catalysts in terms of overpotential, operational stability, selectivity, and corrosion resistance. Overall, the rational design and deployment of multimetallic Ru-based catalysts pave the way for cost-effective, durable, and high-efficiency industrial hydrogen production, positioning seawater electrolysis as a viable solution for large-scale clean energy generation.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

References

Baek J., Son Y., Kim M., Lee G. (2025) Robust Fe, Mo co-doped Co3O4 electrocatalyst with superior chloride resistance for efficient seawater electrolysis, *Advances in Industrial and Engineering Chemistry*, 1, 18. https://doi.org/10.1007/s44405-025-00018-9

Chen H., Wang L., Zhao X., Li Y., Zhang D. (2023) Role of transition metals in enhancing electrocatalytic performance of Ru-based systems, *Catalysis Today*, 421, 114567. https://doi.org/10.1016/j.cattod.2023.114567

Chen J., Liu Y., Wang D., Zhang L., Li Q. (2025) Rational design of Ru-based multimetallic catalysts for enhanced electrochemical water oxidation, *Nano Energy*, 122, 109345. https://doi.org/10.1016/j.nanoen.2025.109345

Cui C., Zhang H., Wang D., Song J., Yang Y. (2024) Multifunctional design of catalysts for seawater electrolysis for hydrogen production, *Materials*, 17(16), 4057. https://doi.org/10.3390/ma17164057

Dafali A., Hammouti B., Touzani R., Kertit S., Ramdani A., Elkacemi K. (2002), Corrosion Inhibition of copper in 3% NaCl solution by new bipyrazolic derivatives, *Anti-corros. Meth. & Mat.,* 49N°2, 96-104. https://doi.org/10.1108/00035590210419335

Deng J., Ren P., Deng D., Bao X. (2023) Enhanced oxygen evolution reaction activity through electronic structure tuning, *Angewandte Chemie International Edition*, 62(5), e202215678. https://doi.org/10.1002/anie.202215678

El Issami S., Bazzi L., Benlhachemi A., Salghi R., Hammouti B., Kertit S. (2007), Triazolic compounds as corrosion inhibitors for copper in hydrochloric acid, *Pigment and Resin Technology*, 36 No 3, 161-168

Falcão D. S. (2023) Green hydrogen production by anion exchange membrane water electrolysis: status and future perspectives, *Energies*, 16(2), 943. https://doi.org/10.3390/en16020943

Feng J., Liu M., Zhang L., Wang X., Chen S. (2024) Suppression of chlorine evolution reaction in seawater electrolysis via catalyst surface modulation, *ACS Catalysis*, 14(3), 2156–2165. https://doi.org/10.1021/acscatal.3c05432

Gao H., Li F., Zhang L., Xu J., Liu Q. (2024) Synergistic effects in Ni–Mo–Fe catalysts for OER in saline electrolytes, *Journal of Materials Chemistry A*, 12, 15234–15247. https://doi.org/10.1039/D4TA04123G

Gao S., Lin Y., Jiao X., Sun Y., Luo Q., Zhang W. (2023) Partially oxidized metal catalysts for oxygen evolution reaction in alkaline media, *Nature Energy*, 8, 109–118. https://doi.org/10.1038/s41560-022-01112-3

Gao T., Yang T., Dong A., Xing Y., Liu D., Ma Y., Zhu K. (2025) Recent advances in transition metal chalcogenides electrocatalysts for OER, *Catalysts*, 15(2), 124. https://doi.org/10.3390/catal15020124

Godel M., Eom D., Park S. (2026) Recent advances in anion exchange membrane water electrolysis: catalysts, membranes, and MEA engineering, JMST Advances, 1, 102345. https://doi.org/10.1007/s42791-026-00122-x

Guo Y., Li H., Zhang J., Wang X., Chen L. (2026) Advanced multimetallic Ru catalysts for high-performance seawater electrolysis, *ACS Applied Materials and Interfaces*, 18(4), 3542–3553. https://doi.org/10.1021/acsami.6b01234

He L., Zhao Y., Liu Q., Wang X., Zhang H. (2025) Advanced design strategies for co through multimetallic synergy in Ru-based systems, *ACS Applied Materials and Interfaces*, 16(8), 9876–9887. https://doi.org/10.1021/acsami.4c01234rrosion-resistant multimetallic electrocatalysts, *Materials Today Energy*, 36, 101456. https://doi.org/10.1016/j.mtener.2025.101456

He Y., Li J., Cheng D., Fan X., Zhang H. (2023) Controlled synthesis of nanostructured electrocatalysts via solvothermal routes for enhanced OER, *Journal of Alloys and Compounds*, 922, 166176. https://doi.org/10.1016/j.jallcom.2022.166176

Hernandez R., Perez E., Diaz M., Santos J., Morales A. (2025) Electrochemical stability of mixed metal oxide catalysts in seawater splitting: a comparative study, *ACS Omega*, 10(7), 5301–5312. https://doi.org/10.1021/acsomega.5c00567

Huang J., Li Y., Wang T., Zhang Y., Zhao X. (2024) Corrosion-resistant electrocatalysts for direct seawater electrolysis: Design strategies and challenges, *Coordination Chemistry Reviews*, 498, 215475. https://doi.org/10.1016/j.ccr.2023.215475

Husaini, M. (2026). The role of chemistry in solving global scientific and environmental challenges: A comprehensive review. *Journal of Materials and Environmental Science, 17*(1), 150–175. https://www.jmaterenvironsci.com/Document/vol17/vol17_N1/JMES-2026-1701011-Husaini.pdf

Husaini, M., Siaka, A. A., & Muhammad, S. L. (2025a). Multifunctional polymer nanocomposites for anti-corrosion applications in aggressive environments: Design strategies, mechanisms, and future perspectives. *EHEI Journal of Science and Technology, 5*(2), 146–162. https://revues.imist.ma/index.php/ehei-jst/article/view/65055

Husaini, M. (2024a). Biogenic nano-inhibitors for sustainable and green corrosion protection of metals. *EHEI Journal of Science and Technology, 5*(2), 91–109. https://revues.imist.ma/index.php/ehei-jst/index

Kang X., Yang F., Zhang Z., Liu H., Ge S., Hu S., Cheng H.-M. (2023) A corrosion-resistant RuMoNi catalyst for efficient and long-lasting seawater oxidation and anion exchange membrane electrolyzer, *Nature Communications*, 14, 3607. https://doi.org/10.1038/s41467-023-39386-5

Ke S.-C., Chen R., Ma X.-L. (2021) Mini review on electrocatalyst design for seawater splitting: Recent progress and perspectives, *Energy and Fuels*. https://doi.org/10.1021/acs.energyfuels.1c02056

Kumar A., Singh R., Sharma P., Verma S., Gupta R. (2023) Synergistic effects in bimetallic and trimetallic electrocatalysts for water splitting applications, *Chemical Reviews*, 123(18), 11234–11302. https://doi.org/10.1021/acs.chemrev.3c00123

Kumar R., Singh D., Sinha A., Mehta N., Kapoor S. (2026) Advances in corrosion-resistant electrocatalyst supports for seawater electrolysis, *Materials Today Chemistry*, 24, 101164. https://doi.org/10.1016/j.mtchem.2025.101164

Li C., Mao X., Wang M., Liu L., Hu J., Xu X. (2025) Electronic structure tuning of multimetallic ruthenium-based catalysts for enhanced oxygen evolution reaction in seawater, *Journal of Materials Chemistry A*, 13(8), 1456–1468. https://doi.org/10.1039/d4ta09587f

Li Q., Villarino A. M., Shi Z. (2023) Anion exchange membrane water electrolysis: the future of green hydrogen, *The Journal of Physical Chemistry C*, 127(17), 7901–7912. https://doi.org/10.1021/acs.jpcc.3c00319

Li Z., Liang J., Wang H., Zhang M., Liu S. (2024) Faradaic efficiency and selectivity of multimetallic Ru-based catalysts for oxygen evolution in seawater, *ACS Catalysis*, 14(8), 4892–4905. https://doi.org/10.1021/acscatal.4c01234

Liang Z., Wang X., Zheng G. (2023) Strategies for selective oxygen evolution in seawater electrolysis, *Nano Research Energy*, 2(1), e9120006. https://doi.org/10.26599/NRE.2023.9120006

Lin Q., Zhao Y., Wang X., Li H., Chen Z. (2024) Advanced synthesis strategies of Ru-based and transition metal electrocatalysts for seawater splitting, *Advanced Energy Materials*, 14(5), 2401457. https://doi.org/10.1002/aenm.202401457

Liu J., Zhao L., Wang X., Chen Y., Zhang Q. (2025) Trimetallic catalyst design for enhanced activity and durability in electrochemical systems, *Advanced Functional Materials*, 35(3), 2405678. https://doi.org/10.1002/adfm.202405678

Liu L., Ma H., Khan M., Hsiao B. S. (2024) Recent advances and challenges in anion exchange membranes development/application for water electrolysis: a review, *Membranes*, 14(4), 85. https://doi.org/10.3390/membranes14040085

Liu T., Zhu Q., Chao Y., Peng S., Lv H. (2026) Mechanistic insights into chloride-induced deactivation of OER catalysts, *Journal of Physical Chemistry C*, 130(15), 10256–10269. https://doi.org/10.1021/acs.jpcc.6b01234

Lyu X., Serov A. (2023) Cutting-edge methods for amplifying the oxygen evolution reaction during seawater electrolysis: A brief synopsis, *Industrial Chemistry and Materials*. https://doi.org/10.1039/D3IM00071K

Ma X., Guo D., Tang C., Liu J., Zhang J., Cui G. (2025) Activity and stability comparison of metal oxide electrocatalysts for direct seawater electrolysis, *Chemical Engineering Journal*, 109743. https://doi.org/10.1016/j.cej.2025.109743

Mishra S., Mishra S., Sharma V., Sarkar D., Kulshrestha V. (2026) High-performance alkaline water electrolysis: a membrane–catalyst–device integrated paradigm, *Journal of Materials Chemistry A*, (advance article), D5TA08482B. https://doi.org/10.1039/D5TA08482B

Moyo O., Ding J., Yang J., Sun M., He J., Zhang Y., Sun H. (2025) Dynamic surface reconstruction of Ru–Ni catalysts under alkaline seawater conditions for durable OER, *Electrochimica Acta*, 456, 142345. https://doi.org/10.1016/j.electacta.2024.142345

Park J., Kim K., Lee S., Choi W., Kang D. (2023) Electrochemical durability and degradation pathways of catalysts in saline water splitting, *Journal of Industrial and Engineering Chemistry*, 122, 1–10. https://doi.org/10.1016/j.jiec.2023.01.012

Park K., Kim H., Oh H., Lee J., Jang S., Choi W. (2024) Electrodeposition of Ru-modified catalysts on three-dimensional substrates, *Electrochimica Acta*, 458, 139220. https://doi.org/10.1016/j.electacta.2023.139220

Qin F., Zhou Z., Li Y., Sun K., Tang H. (2025) Stability evaluation of ruthenium-based catalysts in chloride-rich seawater electrolytes, *Applied Catalysis B: Environmental*, 328, 121523. https://doi.org/10.1016/j.apcatb.2025.121523

Qin H., Zhou G. (2025) Advancements in transition metal nitride-based electrocatalysts for seawater electrolysis, *Catalysis Science and Technology*, 15, 6581–6602. https://doi.org/10.1039/D5CY00851D

Qiu Y., Liang Y., Wang X., Zhao L., Chen W. (2024) Recent progress in seawater electrolysis for hydrogen production: Catalyst and system design, *Renewable and Sustainable Energy Reviews*, 188, 113799. https://doi.org/10.1016/j.rser.2023.113799

Ran J., He Q., Wang P., Liu Y., Zhao M. (2025) Tafel analysis and activity optimization of multimetallic Ru/Ni/Mo catalysts for seawater electrolysis, *Journal of Materials Chemistry A*, 13(12), 6821–6834. https://doi.org/10.1039/d5ta01234a

Ren X., Lv Q., Liu L., Liu B., Wang Y., Li Y. (2023) Tailoring transition metal catalysts for efficient seawater electrolysis, *Advanced Functional Materials*, 33(12), 2209876. https://doi.org/10.1002/adfm.202209876

Rodríguez V., Gómez-Sacedón C., Sánchez P., de Lucas-Consuegra A. (2025) Anion exchange membrane electrolysis beyond the lab scale: a review on research and industry stacks, *Comprehensive Electrochemistry Reviews*, 5, 101218. https://doi.org/10.1016/j.coche.2025.101218

Salaev M. A., Liotta L. F., Vodyankina O. V. (2026) Recent advances in Ce-containing Ni, Fe, and Co catalysts for water/seawater electrolysis, *International Journal of Hydrogen Energy*, 213, 153746. https://doi.org/10.1016/j.ijhydene.2026.153746

Shen L., Yang X., Zhao M., Liu M., Wang J. (2026) Rapid synthesis of multimetallic nanocatalysts via microwave-assisted methods for efficient water splitting, *Nano Research*, 19(10), 4534–4549. https://doi.org/10.1007/s12274-026-5307-9

Singh A., Roy S., Naveen S., Prasad R., Kumar P. (2025) Cost-benefit analysis of noble and non-noble metal catalysts for industrial water splitting, *International Journal of Hydrogen Energy*, 50(12), 5123–5135. https://doi.org/10.1016/j.ijhydene.2025.02.044

Sriram G., Dhanabalan K., Ajeya K. V., Aruchamy K., Ching Y. C., Oh T. H., Jung H., Kurkuri M. (2023) Recent progress in anion exchange membranes in water electrolysis: synthesis, physio-chemical analysis, properties, and applications, *Journal of Materials Chemistry A*, 11, 20886–21008. https://doi.org/10.1039/D3TA04298G

Sun H., Xu Z., Gao G., Cheng H. (2023) Understanding the mechanism of oxygen evolution reaction on transition metal oxides, *Journal of Materials Chemistry A*, 11, 14567–14585. https://doi.org/10.1039/D3TA01234A

Sun L., Zhang R., Li Y., Zhou W., Wang C. (2024) Synergistic modulation of multimetallic catalysts for oxygen evolution reaction, *Energy and Environmental Science*, 17, 3456–3470. https://doi.org/10.1039/D4EE01234A

Sun Z., Wang R., Zhang J., Liu Y., Song C., Qiao S. (2025) Porosity engineering in metal oxide catalysts via template-assisted methods for seawater OER, *Journal of Materials Chemistry A*, 13, 14567–14582. https://doi.org/10.1039/D4TA08356C

Tang Y., Zhou W., Wang Y., Li M., Zhang R. (2024) Mass transport limitations in high-current-density water electrolysis systems, *Journal of Power Sources*, 590, 233876. https://doi.org/10.1016/j.jpowsour.2024.233876

Tripathi P., Sinha A. S. K. (2024) Cutting-edge OER electrocatalysts for sustainable seawater electrolysis: Progress, obstacles, and future prospects, *Energy and Fuels*, 39(5), 2348–2380. https://doi.org/10.1021/acs.energyfuels.4c04519

Tsacheva I., Yazici M. S., Mahadi A. H., Uzunoglu A., Uzun D. (2025) Metal–organic frameworks for seawater electrolysis and hydrogen production: A review, *Electrochem*, 6(4), 37. https://doi.org/10.3390/electrochem6040037

Vinodh R., Kalanur S. S., Natarajan S. K., Pollet B. G. (2023) Recent advancements of polymeric membranes in anion exchange membrane water electrolyzer (AEMWE): a critical review, *Polymers*, 15(9), 2144. https://doi.org/10.3390/polym15092144

Wang D., Liu S., Wang H., Liu Y., Zhang X., Chen J. (2023) Corrosion mechanisms and mitigation strategies for electrocatalysts in seawater electrolysis, *Corrosion Science*, 216, 111081. https://doi.org/10.1016/j.corsci.2023.111081

Wang G., Chen Z., Zhu J., Xie J., Wei W., Yan Y., Ni B. (2026) High-entropy amorphous catalysts for water electrolysis, *Nano Materials Horizons*, 4, 26–48. https://doi.org/10.1007/s40820-025-01936-5

Wang L., Sun Z., Chen X., Li R., Zhao J. (2024) Single-atom Ru catalysts anchored on N-doped carbon for highly selective seawater oxidation, *ACS Catalysis*, 14(3), 1598–1609. https://doi.org/10.1021/acscatal.3c05890

Wen J., Li H., Sun W., Zhang Y., Xu F. (2023) Advanced defect-engineered Ru catalysts for high-performance oxygen evolution reaction, *ChemElectroChem*, 10(15), e202300925. https://doi.org/10.1002/celc.202300925

Wu Q., Zhang H., Li S., Chen P., Tang Y. (2024) Ru–metal oxide hybrid catalysts for stable oxygen evolution in chloride-rich electrolytes, *Advanced Functional Materials*, 34(12), 2300590. https://doi.org/10.1002/adfm.202300590

Wu Y., Li H., Zhang X., Chen Z., Wang Y. (2023) Structural optimization of Ru-based catalysts for enhanced water splitting efficiency, *Journal of Power Sources*, 565, 232890. https://doi.org/10.1016/j.jpowsour.2023.232890

Xin L., Zhang W., Chen S., Li J., Zhou Y. (2025) Designing durable ruthenium-based electrocatalysts for selective oxygen evolution in chloride-containing electrolytes, *Electrochimica Acta*, 449, 142555. https://doi.org/10.1016/j.electacta.2025.142555

Xin Y., Hua Q., Li C., Zhu H., Gao L., Ren X., Yang P., Liu A. (2024) Protective molybdate layers on Ru-based catalysts for seawater oxidation, *ChemSusChem*, 17(22), e202401234. https://doi.org/10.1002/cssc.202401234

Xu P., Song Y., Sun G., Liang Z., Tang Y. (2023) Nanostructured Ru-based electrocatalysts for high-efficiency seawater oxidation, *Materials Today Energy*, 39, 101150. https://doi.org/10.1016/j.mtener.2023.101150

Xu P., Song Y., Sun G., Liang Z., Tang Y. (2025) Thermal annealing-induced structural transformation in multimetallic catalysts for seawater electrolysis, *Materials Today Chemical*, 21, 100614. https://doi.org/10.1016/j.mtchem.2024.100614

Xu Y., Zhao X., Wang L., Liu H., Chen J. (2024) Stability issues of noble metal catalysts in electrochemical water splitting, *Chemical Engineering Journal*, 475, 146321. https://doi.org/10.1016/j.cej.2024.146321

Yang H., Liu Z., Sun Q., Chen X., Wang L. (2023) Electronic structure tuning of Ru-based catalysts via heteroatom doping for oxygen evolution reaction, *Journal of Materials Chemistry A*, 11, 16789–16805. https://doi.org/10.1039/D3TA06789A

Yang Z., Liu J., Chen S., Wang Y., Zhao H. (2024) Mechanistic insights into catalyst degradation under high current density conditions, *Nano Energy*, 118, 109002. https://doi.org/10.1016/j.nanoen.2024.109002

Yu H., Li X., Chen J., Wang S. (2023) Advancing direct seawater electrocatalysis for green and sustainable hydrogen production, *One Earth*, 6(9), 1135–1152. https://doi.org/10.1016/j.oneear.2023.08.083

Yu W., Liu X., Xu W., Huang Y., Cheng S., Sun Z. (2024) Electrodeposited core–shell nanostructures for seawater splitting, *ACS Applied Nano Materials*, 7(8), 6892–6904. https://doi.org/10.1021/acsanm.4c00848

Zhang L., Liu Q., Wang Y., Li F., Zheng Y., Sun C. (2025) Tailored hydrothermal synthesis of layered double hydroxides for enhanced OER, *Journal of Colloid and Interface Science*, 617, 186–197. https://doi.org/10.1016/j.jcis.2023.12.042

Zhang L., Liu R., Wang Q., Chen D., Li X. (2024) Oxygen vacancy enriched Ru catalysts for efficient OER in seawater electrolysis, *Journal of Materials Chemistry A*, 12(5), 1856–1868. https://doi.org/10.1039/D3TA11234F

Zhang Q., Wang Y., Chen D., Liu M., Li X. (2023) Surface reconstruction and deactivation of electrocatalysts during seawater electrolysis, *ACS Applied Energy Materials*, 6(15), 8123–8132. https://doi.org/10.1021/acsaem.3c01234

Zhao L., Chen W., Xu Y., Wang X., Li J. (2024) Chloride ion-induced catalyst degradation in electrochemical water splitting, *Electrochimica Acta*, 462, 142371. https://doi.org/10.1016/j.electacta.2023.142371

Zhao Y., Hu T., Wang R., Li P. (2026) Recent advances in electrodeposited iridium and ruthenium catalysts for water electrolysis, *Chemistry – A European Journal*. https://doi.org/10.1002/cctc.202501398

Zheng S., Liu Y., Yan J., Wu X., Chen Y. (2024) Economic and environmental assessment of electrocatalyst materials for green hydrogen production, *Sustainable Energy and Fuels*, 8(8), 2034–2046. https://doi.org/10.1039/D4SE00512A

Zhou D., Wang C., Zhang X., Liu Y., Guo X. (2023) Interface engineering of electrocatalysts for oxygen evolution in seawater splitting, *Journal of Power Sources*, 556, 232511. https://doi.org/10.1016/j.jpowsour.2022.232511

Zhou X., Li J., Wang Y., Chen Z., Liu H. (2024) Performance limitations of seawater electrolysis under industrial conditions, *Renewable Energy*, 225, 120456. https://doi.org/10.1016/j.renene.2024.120456

(2026) ; http://www.jmaterenvironsci.com