OPEN ACCESS

Saudi Journal of Engineering and Technology

Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) |ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Review Article

Nickel-Based Electrocatalysts for Alkaline Water Electrolysis: Catalyst Design, Activity-Stability Trade-Offs, and Industrially Relevant Hydrogen Production

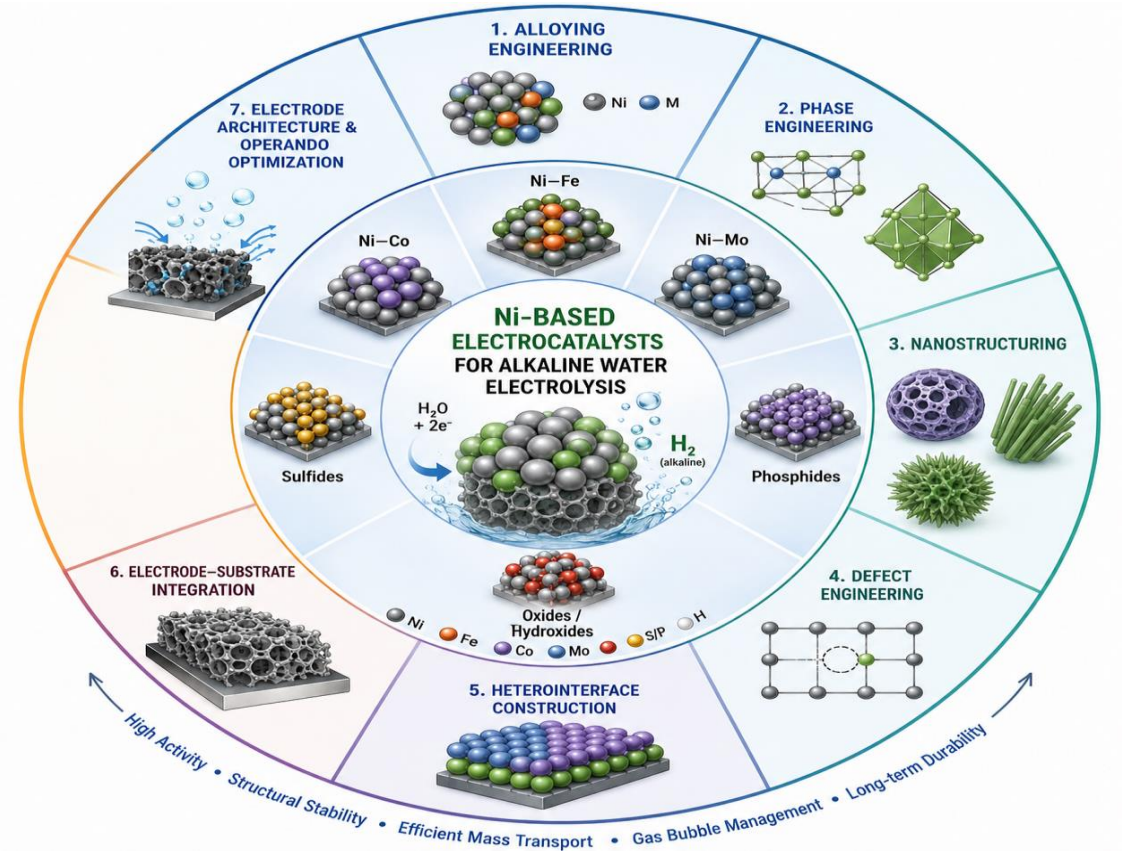
Manahil Rubab[1]*, Duaa Fatima[1], Hijab Zahra[1]

[1]Thal University Bhakkar, Pakistan

DOI: https://doi.org/10.36348/sjet.2026.v11i09.012 | **Received:** 06.07.2026 | **Accepted:** 31.08.2026 | **Published:** 24.09.2026

***Corresponding author:** Manahil Rubab
Thal University Bhakkar, Pakistan

Abstract



Graphical abstract

Nickel-based electrocatalysts have emerged as important alternatives to precious metal catalysts for alkaline water electrolysis because of their abundance, relatively low cost, electrical conductivity, and compatibility with alkaline operating environments. Considerable progress has been achieved through alloying, phase engineering, nanostructuring, defect generation, heterointerface construction, and electrode–substrate integration, particularly in Ni–Co, Ni–Mo, nickel sulfide, nickel phosphide, nickel oxide, and nickel hydroxide. However, reported improvements in electrocatalytic activity do not necessarily translate into efficient and durable hydrogen production under practical operating conditions. This

review critically examines the relationship between Ni-based catalyst composition, structure, electrochemical reconstruction, catalytic activity, and long-term stability in alkaline water electrolysis. Attention is given to the dynamic transformation of Ni-containing surfaces during operation, the influence of Fe, Co, and Mo incorporation, structural and interfacial engineering, and the effects of catalyst architecture on mass transport and gas-bubble management. This critical review further evaluates the limitations of conventional low-current-density catalyst screening. It emphasizes high-current-density performance, full-cell voltage, Faradaic efficiency, electrode integrity, and long-term durability as more meaningful indicators of practical performance. Finally, it discusses the challenges associated with operating-state characterization, standardized testing, dynamic operation, scalable electrode fabrication, and translation from laboratory electrodes to practical electrolyzers. By connecting catalyst design with electrode engineering and electrolyzer-level performance, this review provides a framework for developing Ni-based electrodes capable of combining high activity, structural stability, and sustained hydrogen production under industrially relevant alkaline electrolysis conditions.

Keywords: Nickel-based electrocatalysts; alkaline water electrolysis; hydrogen evolution reaction; oxygen evolution reaction; activity–stability trade-off; high-current-density electrolysis; electrode engineering; green hydrogen.

1. INTRODUCTION

The increasing integration of renewable energy has created a growing demand for efficient methods of storing renewable electricity in the form of chemical fuels. Green hydrogen produced by water electrolysis is particularly attractive because it can provide a low-carbon energy carrier and support the decarbonization of energy-intensive sectors. [1–3] However, the efficiency, cost, and durability of electrolyzers remain important barriers to large-scale hydrogen production.

Among the available electrolysis technologies, alkaline water electrolysis (AWE) is one of the most established approaches for large-scale hydrogen production. Its use of an alkaline liquid electrolyte and relatively inexpensive non-precious electrode materials provide important economic advantages. [1, 2, 4] Nevertheless, conventional AWE is limited by electrode kinetics, ohmic losses, gas-bubble accumulation, mass-transport limitations, and degradation, particularly when operation is extended toward higher current densities.

These challenges have stimulated extensive development of nickel-based electrocatalysts. Nickel combines alkaline compatibility, electrical conductivity, and broad compositional tunability, enabling Ni–Fe, Ni–Co, Ni–Mo, multimetallic, sulfide, phosphide, oxide, and hydroxide platforms. Recent work further demonstrates that performance can be altered by alloying, defect engineering, heterointerface construction, electrodeposition, direct growth, and electrode architecture. [1–3, 5–24] Recent work shows that NiFe catalysts can exhibit measurable Fe dissolution while Ni remains largely stable toward ionic dissolution. Despite this progress, comparing Ni-based catalysts remains challenging because reported overpotentials and Tafel slopes depend strongly on catalyst loading, substrate, electrolyte, iR compensation, activation procedure, and current-density normalization. More importantly, Ni-based surfaces can reconstruct, redistribute elements, and undergo dissolution during operation [36–41]. Recent work shows that NiFe catalysts can exhibit measurable Fe dissolution while Ni remains largely stable toward ionic dissolution, demonstrating why post-operando characterization is essential for interpreting durability [34]. The recent perspective on Ni anodic electrocatalysis likewise emphasizes dynamic Ni oxidation-state changes and reconstruction toward NiOOH-like or Ni oxyhydroxide-rich operating surfaces [35]. Consequently, this review evaluates activity together with characterization, stability, electrode architecture, and high-current-density operation rather than treating the lowest overpotential as a universal ranking criterion.

Importantly, excellent activity at conventional laboratory current densities does not necessarily translate into practical hydrogen production. At higher current densities, gas evolution, mass transport, ohmic losses, electrode integrity, and catalyst stability become increasingly important. [2, 15, 16, 32, 34, 43–45, 49–53] A meaningful evaluation of Ni-based electrocatalysts therefore requires simultaneous consideration of activity, stability, electrode architecture, mass transport, and high-current-density performance, rather than relying on overpotential alone.

Accordingly, this review provides a catalyst-centered critical assessment of nickel-based electrocatalysts for alkaline water electrolysis. Ni–Fe, Ni–Co/Ni–Fe–Co, Ni–Mo and other Ni-based alloys, nickel sulfides/phosphides, and nickel oxides/hydroxides/spinels are examined through composition, structural engineering, catalytic activity, operating-state reconstruction, stability and practical electrode performance. Attention is given to the activity–stability trade-off and to the evidence needed to translate laboratory-scale catalyst improvements into high-current-density, scalable hydrogen production.

2. Fundamentals of Nickel-based alkaline water electrolysis:

Alkaline water electrolysis couples the hydrogen evolution reaction (HER) at the cathode with the oxygen evolution reaction (OER) at the anode, with OH^- serving as the principal charge carrier. For Ni-based electrodes, catalytic performance is best interpreted through a combination of electrochemical activity and electrode-level behavior rather than a single overpotential value. [4, 47] The key descriptors used throughout this review are overpotential at a defined

current density, Tafel slope, electrochemically accessible surface area (ECSA/Cdl), charge-transfer resistance (Rct), Faradaic efficiency (FE), full-cell voltage, and durability.

The numerical context is essential because reported values depend strongly on catalyst loading, substrate, electrolyte, iR compensation, activation protocol, and current-density normalization. A catalyst delivering a low overpotential at 10 mA cm^{-2} cannot automatically be considered superior to one demonstrated at 100–500 mA cm^{-2} or in a complete electrolyzer. [15, 16, 25, 34, 35, 43, 49–51, 54] Accordingly, the catalyst sections below use quantitative electrochemical data together with XRD, XPS, SEM/TEM, EDS mapping, EIS, ECSA, and post-electrolysis or operando evidence where reported, with particular attention to whether improved activity reflects intrinsic kinetics, greater accessible area, or changes in the operating-state catalyst.

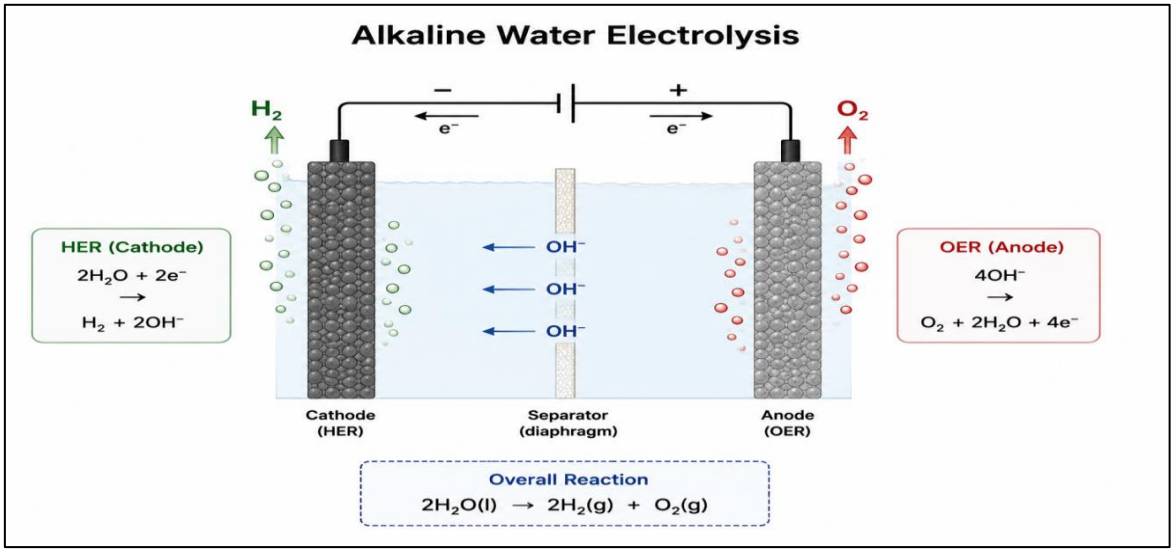


Figure 1: Illustrating the mechanism of alkaline water electrolysis, detailing the electrochemical reaction at electrodes separated by a porous diaphragm

Cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

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

$Overall: 2H_2O \rightarrow 2H_2 + O_2$

3. Nickel-based electrocatalysts for alkaline water electrolysis:

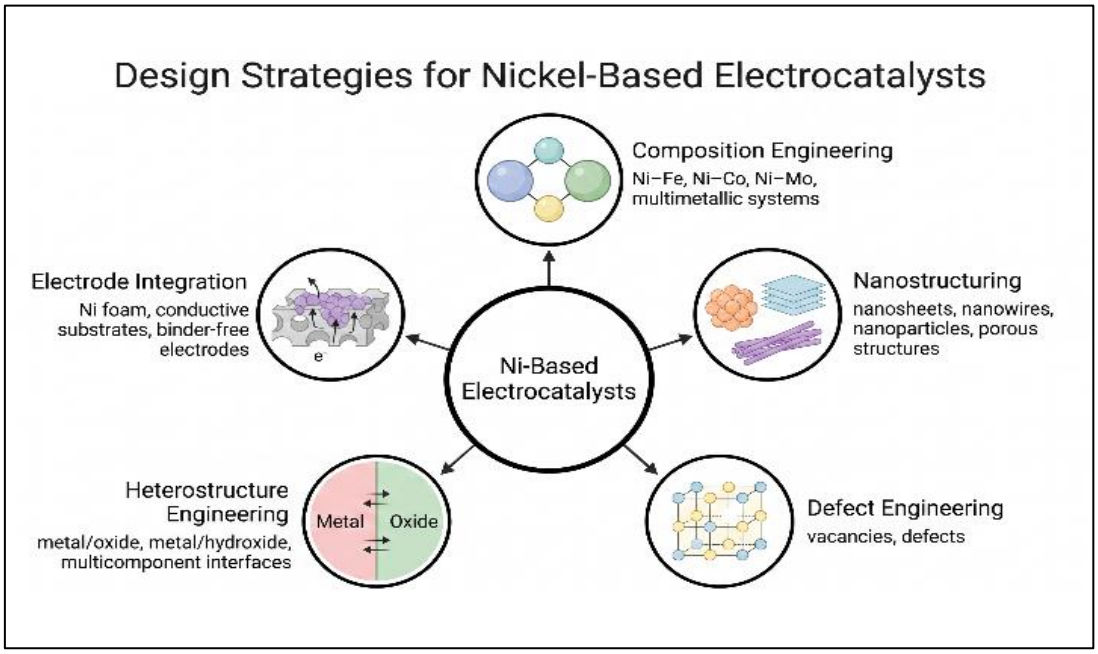


Figure 2: Schematic illustration summarizing key design strategies for nickel-based electrocatalysts to enhance overall water splitting efficiency

3.1 Ni–Fe-based electrocatalysts:

Ni–Fe materials provide the clearest example of why Ni-catalyst assessment must combine quantitative electrochemistry with structural evidence. In 1.0 M KOH, NiFe-LDH-4 reported an OER overpotential of 175 mV at 10 mA cm^{-2} and 235 mV at 50 mA cm^{-2}, with a Tafel slope of 80.32 mV dec^{-1}. The same study reported 96.5 mV HER overpotential at 10 mA cm^{-2} and a 66.97 mV dec^{-1} Tafel slope. [10, 14, 34, 55–60] These values place NiFe-LDH-4 among the stronger bifunctional Ni-based systems in the supplied literature, but the comparison is meaningful only because the current densities and electrolyte are specified

The electrochemical data are supported by measurements that help separate accessible surface area from charge-transfer effects. For OER, NiFe-LDH-4 showed Cdl = 0.149 mF cm^{-2} and Rct = 0.454 Ω cm^{-2}, while the corresponding Cdl values for NiFe-LDH-1, -2 and -6 were 0.093, 0.101 and 0.148 mF cm^{-2}, respectively. Its lower Rct and larger Cdl are consistent with improved interfacial charge transfer and greater electrochemically accessible area, indicating that the low overpotential cannot be assigned to Fe incorporation alone. [27, 42, 55, 56, 58–60, 61, 62] SEM/TEM showed interconnected nanosheets within nanospheres, HRTEM gave a 0.254 nm lattice spacing, and EDS mapping showed relatively uniform Ni/Fe distribution. These measurements provide a stronger structure–performance argument than polarization data alone.

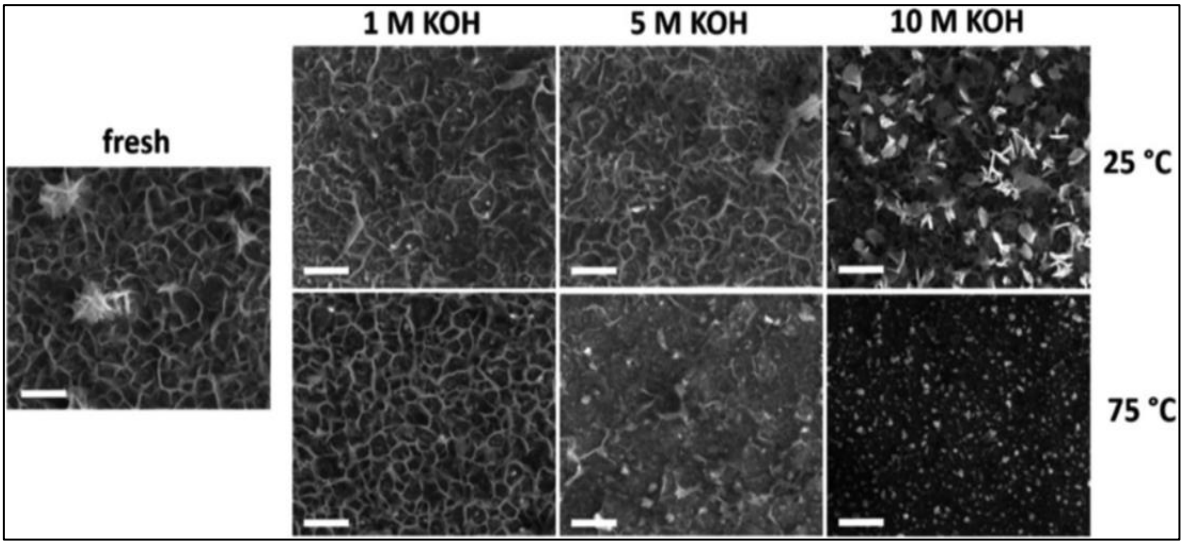


Figure 3: Effect of electrolyte conditions on morphology degradation. SEM images of fresh and used NiFe-LDH catalyst films on Au after the stability tests conducted at 100 mA cm–2 for 1 h at different temperatures and electrolyte concentrations (scale bars 500 nm). Reproduced from Ref. [63] with permission from the Royal Society of Chemistry. Copyright 2020

The stability evidence is equally important. After 12 h of cycling, the reported overpotentials at 50 and 100 mA cm^{-2} remained nearly unchanged, while post-cycling XPS, SEM, and TEM showed only limited morphological change. XPS indicated an increased Ni^{3+}/Ni^{2+} ratio and greater M–OH contribution after OER, whereas the HRTEM lattice spacing changed by only about 0.004 nm and EDS continued to show a uniform Ni/Fe distribution. This suggests that activation involves surface chemical evolution toward an oxyhydroxide-rich state without complete structural collapse. [10, 53, 64] The implication is that the as-synthesized NiFe-LDH should not be treated as identical to the operating catalyst; the electrochemically generated surface is part of the catalyst's functional identity

The Fe effect therefore represents an activity–stability trade-off rather than a simple monotonic composition rule. Increasing Fe can improve OER kinetics, but the optimum composition depends on Fe distribution and the surface state generated during operation. [14, 42, 55, 56, 58] This is why concentration-dependent studies should be interpreted alongside post-electrolysis composition and potential evolution, rather than comparing only initial overpotentials.

The practical significance becomes clearer at higher current density. NiFe-LDH-4 required 476.3 mV OER overpotential and 401.7 mV HER overpotential at 500 mA cm^{-2} in alkaline conditions and retained its OER current for 50 h at 500 mA cm^{-2}. [44, 45, 55, 56, 58] In an AEM electrolyzer, a NiFe-LDH-4@NF‖NiFe-LDH-4@NF cell reached 1.725 V at 10 mA cm^{-2} and showed almost no potential change over 27 h. Thus, the same catalyst demonstrates a much larger polarization penalty when moving from 10 to 500 mA cm^{-2}, illustrating why

low-current overpotential alone can exaggerate practical differences among materials.

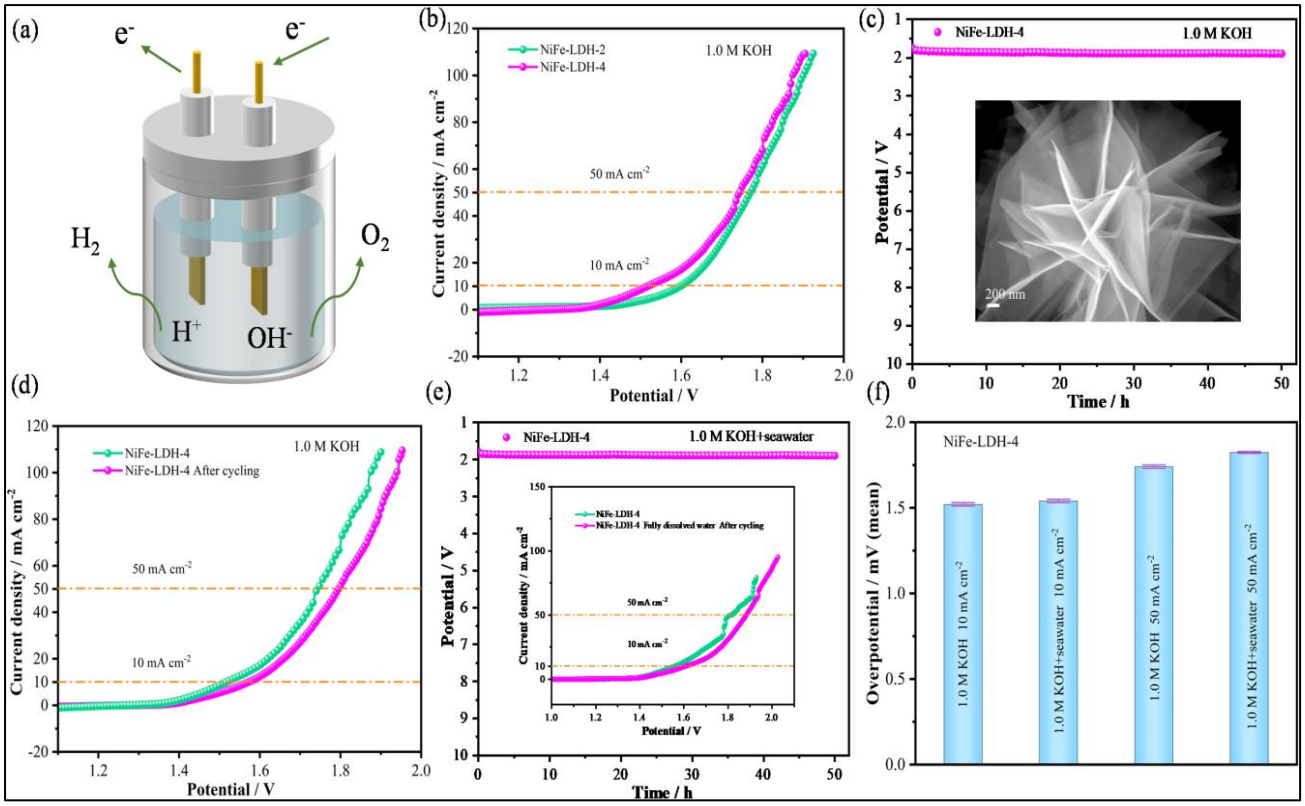


Figure 4: Practical AEM water-electrolysis performance of NiFe-LDH, showing electrolyzer configuration, polarization behavior, and long-term operation. Reproduced/adapted from Ref. [10] under the applicable licence

Overall, Ni–Fe remains a strong alkaline OER platform, but its advantage arises from the combined effects of composition, accessible morphology, interfacial charge transfer, and operating-state reconstruction. [34, 42, 53, 55–60, 64] The more convincing studies are therefore those that report quantitative activity at multiple current densities and connect those values to XPS/TEM/EDS/EIS evidence and long-duration operation.

3.2 Ni–Co and Ni–Fe–Co multimetallic electrocatalysts:

Ni–Co and Ni–Fe–Co systems expand the compositional space for tuning alkaline electrocatalysis, but the supplied literature provides a more limited quantitative basis for direct comparison than for Ni–Fe. A representative NiCo-LDH benchmark reports an OER overpotential of 303 mV at 50 mA cm^{-2} in 1.0 M KOH and an HER overpotential of 227 mV in the same electrolyte. [65, 72, 81, 84, 88] In the same literature comparison, NiFe-LDH is listed at 175 mV for OER and 185 mV for HER, but the OER values are not measured at the same current density; therefore, these numbers should not be treated as a ranking. The key point is that Ni–Co modification can produce useful bifunctional activity, but its advantage must be demonstrated under matched current density and electrode conditions rather than inferred from composition alone.

The quantitative evidence should also be connected to characterization. For Ni–Co/Ni–Fe–Co electrodes, XRD is needed to establish phase constitution, XPS to determine Ni/Co/Fe oxidation states and their evolution, and SEM/TEM with EDS mapping to distinguish genuine compositional integration from phase segregation. Cdl/ECSA and EIS are particularly important because a lower overpotential can arise from greater accessible area or lower interfacial resistance rather than a purely electronic effect. Where the supplied studies do not report FE, high-current polarization, or post-electrolysis composition, that absence should be treated as a limitation rather than used to claim superior practical performance.

The critical issue for multimetallic Ni catalysts is therefore whether the additional element produces a measurable kinetic benefit that survives reconstruction and remains useful at elevated current density. [61, 66, 67] Increasing compositional complexity can also make the active phase more difficult to identify and reproducibly fabricate. Ni–Fe–Co systems should consequently be judged by matched-condition activity, quantitative transport/kinetic measurements, structural retention and, ideally, full-cell validation rather than by the number of elements incorporated.

3.3 Ni–Mo and other Ni-based alloy electrocatalysts:

Ni–Mo alloys are primarily attractive for alkaline HER, where the Ni component can assist water activation while Mo modifies hydrogen-related surface chemistry. [13, 18–20, 32] In the supplied literature, however, the strongest evidence for this family is its emphasis on electrode-level behavior rather than a single universally representative overpotential value. This is important because Ni–Mo performance depends strongly on alloy state, surface composition, catalyst loading, and substrate architecture. Accordingly, a reported low HER overpotential should be interpreted together with Tafel slope, Cdl/ECSA, Rct, and the current density at which the value was obtained.

The practical evidence is particularly important. The supplied literature identifies electrode architecture and mechanical integrity as limiting factors near 1000 mA cm^{-2}, where conventional deposited catalyst layers can experience cracking or exfoliation. This changes the interpretation of Ni–Mo activity: an alloy may exhibit favorable half-cell kinetics but still be unsuitable for sustained high-rate hydrogen production if adhesion, gas removal, or transport deteriorates. The relevant comparison is therefore not simply Ni–Mo versus Ni, but catalyst composition together with the electrode architecture that allows the composition to remain functional at high rate.

For Ni–Mo, the most convincing evidence would combine overpotential at several current densities with Tafel slope, catalyst loading, Cdl/ECSA, Rct, FE, full-cell voltage, and post-electrolysis elemental analysis. [25, 32, 45, 52, 87–88, 96, 101] In the absence of these measurements, the review should avoid assigning the observed activity solely to Mo-induced electronic effects. Instead, the literature should be interpreted as showing promise for alkaline HER while leaving the relative contributions of intrinsic kinetics, accessible area, surface reconstruction, and electrode architecture incompletely resolved.

3.4 Nickel sulfide- and phosphide-based electrocatalysts:

Nickel sulfides and phosphides provide another route for modifying the electronic structure of Ni-based electrodes, particularly for HER. A representative $Ni_2P/NiCr(OH)_2$ nanosheet electrode in the supplied 2026 study required 111 mV at 10 mA cm^{-2} for HER, while its charge-transfer resistance decreased to 0.27 Ω compared with 0.53 Ω for Ni_2P alone. The hybrid demonstrated long-term stability for 800 h at 200 mA cm^{-2} in the reported sulfide-oxidation-coupled hydrogen-production configuration. These data support an interfacial contribution to the activity rather than simply attributing the improvement to the Ni_2P phase. Because the anodic reaction is sulfide oxidation (SOR), these results should not be treated as conventional OER water-splitting performance.

The characterization provides unusually useful mechanistic evidence for this catalyst family. XPS showed a 0.7 eV negative shift in the Ni 2p spectrum after coupling Ni_2P with $NiCr(OH)_2$, consistent with electronic interaction between the two components; P–M bonding was also observed together with surface P–O species, indicating partial surface oxidation. In situ ATR-FTIR and Raman measurements further probed interfacial water and reaction intermediates. The reported SOR Tafel slope decreased from 65.3 mV dec^{-1} for Ni_2P to 24.3 mV dec^{-1} for $Ni_2P/NiCr(OH)_2$, while the assembled hybrid system operated for 800 h. [22, 23, 26, 29, 36, 37, 68, 69, 73, 77, 84, 90, 92, 100] Because the anodic reaction in this study is sulfide oxidation rather than conventional OER, the 800 h result should not be presented as direct evidence of conventional alkaline water-splitting durability; its value lies in demonstrating the benefit of interfacial and operando characterization

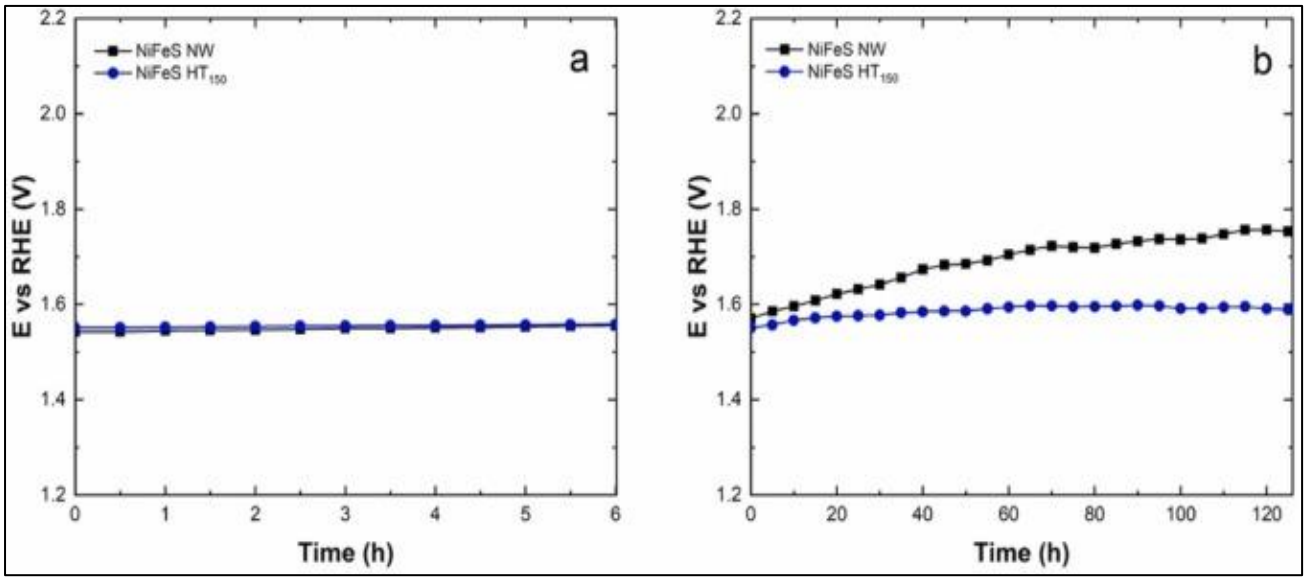


Figure 5: Long-term alkaline OER stability of NiFeS nanowire electrodes at 50 mA cm⁻². (a) Short-term and (b) 125 h stability measurements comparing untreated and thermally stabilized NiFeS electrodes. Reproduced/adapted from Ref. [42] under the applicable licence

The principal limitation of sulfide/phosphide systems is therefore chemical persistence. Surface oxidation or reconstruction can generate the species responsible for activity, while continued sulfur or phosphorus redistribution may alter the catalyst during operation. The strongest studies consequently combine initial phase characterization with XPS, Raman/FTIR, or other operando methods, elemental-retention measurements, current-density-dependent activity, and long-duration testing. [37, 64, 69] Where FE or conventional OER data are absent, those omissions should be stated explicitly rather than treating precursor-phase activity as proof of practical water-electrolysis performance.

3.5 Nickel oxides, hydroxides, and spinel electrocatalysts:

Nickel oxides, hydroxides and mixed-metal spinels are particularly relevant to alkaline OER because their surface chemistry is compatible with the hydroxide/oxyhydroxide environments generated during anodic polarization. The supplied NiFe-LDH evidence illustrates why this family must be interpreted dynamically: after electrolysis, XPS showed an increased Ni^{3+}/Ni^{2+} ratio and greater M–OH contribution, while TEM retained the nanosphere morphology and the HRTEM lattice spacing changed by only about 0.004 nm. Thus, substantial surface chemical evolution can occur without complete morphological collapse. The important question is not simply which precursor phase has the lowest overpotential, but whether the operating-state surface remains active and stable

For oxide/hydroxide/spinel systems, quantitative comparison should therefore combine overpotential and Tafel slope with Cdl/ECSA, Rct, catalyst loading, and current density, followed by pre- and post-electrolysis XPS, XRD, and microscopy where available. [53, 55, 56, 59, 60, 62, 66, 70, 71] A high Cdl can indicate greater accessible area but does not by itself establish higher intrinsic activity; similarly, a low Rct supports efficient charge transfer but does not prove selectivity or long-term durability. The supplied literature also indicates that mixed oxides and spinels offer compositional and structural flexibility, but the evidence is less uniform across studies than for Ni–Fe. Accordingly, claims of superiority should be limited to the metrics actually reported, with FE, high-current performance, and full-cell data identified as missing where applicable.

3.6 Integrated critical comparison: activity, stability, electrode architecture and practical operation

The quantitative evidence illustrates why no single Ni-based family can be ranked by overpotential alone. NiFe-LDH-4, for example, moved from 175 mV at 10 mA cm⁻² to 476.3 mV at 500 mA cm⁻² for OER, while an AEM cell using the same electrode reached 1.725 V at 10 mA cm⁻². [55, 58, 59, 69] In contrast, the $Ni_2P/NiCr(OH)_2$ system demonstrated 111 mV at 10 mA cm⁻² for HER and a 0.27 Ω charge-transfer resistance, but its long-duration validation was performed in a hybrid sulfide-oxidation configuration rather than conventional overall water splitting. These examples are not directly interchangeable; they show that current density, reaction, cell configuration, and stability duration must remain attached to every numerical comparison.

The most defensible comparison therefore combines five dimensions: activity at defined current density, kinetic response (Tafel slope/Rct), accessible active area (Cdl/ECSA), chemical/structural retention during operation, and electrode-level performance including FE, full-cell voltage, and durability. [39–45, 49–54, 56–58, 64] Where one of these dimensions is missing, the literature should be treated as incomplete rather than assigning a categorical ranking. This approach also prevents complex nanostructures or multimetallic compositions from being favored solely because they produce a lower initial overpotential.

4. From laboratory catalysts to industrially relevant hydrogen production:

Catalyst-level activity is only the first step toward practical hydrogen production. Once Ni-based materials are incorporated into an electrode and operated in a complete electrolyzer, cell voltage, gas removal, transport, mechanical integrity, and long-term degradation become coupled. [50, 52, 53] Section 6 therefore evaluates the transition from promising laboratory catalysts to practical alkaline electrolyzer performance rather than repeating catalyst-family comparisons.

4.1 High current-density and full-cell performance:

High current density is a critical discriminator between laboratory screening and practical electrolysis. Increasing the production rate intensifies charge-transfer demand, ionic transport, water supply, gas-bubble formation and detachment, ohmic losses, local heating, and catalyst degradation. Consequently, low-current half-cell measurements cannot by themselves establish practical superiority.

For Ni-based electrodes, high-current performance should therefore be reported together with electrode configuration, catalyst loading, gas-management behavior, stability duration, and full-cell voltage. The latter is particularly important because the energy required for hydrogen production depends on the

combined HER and OER kinetics together with ohmic and transport losses. [87–91, 93–95]

4.2 Electrode architecture, mass transport, and mechanical integrity:

At high production rates, catalyst performance becomes inseparable from electrode architecture. Nickel foam, nickel mesh, porous electrodes, nanowire arrays, and directly grown catalyst layers can improve electrical connectivity and electrolyte access, but excessive porosity or thick catalyst layers can also promote gas retention and transport limitations. Direct growth or electrodeposition can additionally improve catalyst–substrate contact and reduce the need for polymeric binders.

Catalyst loading must be optimized rather than maximized. Increasing loading can raise the number of nominal active sites, but thick or poorly connected layers may contain material that is inaccessible to electrolyte or electrically underutilized. [88, 93, 97–99, 101] Practical electrodes therefore require a balance among active-site accessibility, conductivity, electrolyte transport, gas removal, and mechanical integrity.

4.3 Durability under steady-state and dynamic operation:

Long-term durability is a decisive requirement for green hydrogen production. Ni-based electrodes can experience reconstruction, elemental redistribution, dissolution, mechanical damage, and changes in wetting or gas-management behavior during prolonged operation. These processes may be intensified when electrolyzers are coupled to intermittent renewable electricity, where current density and operating conditions fluctuate.

Stability tests should therefore move beyond short chronoamperometric measurements and report the operating current density, duration, electrolyte conditions, electrode area, and changes in composition or structure where possible. Dynamic start–stop and variable-load testing is also valuable because a catalyst that remains stable at constant current may respond differently to repeated transients. The cross-family quantitative evidence is summarized in Table 1.

4.4 Barriers to scale-up and standardized evaluation:

The principal challenge is not the lack of highly active Ni-based materials, but the difficulty of determining which laboratory improvements remain meaningful at electrode and electrolyzer scale. [85, 87–91] Differences in catalyst loading, substrate, electrolyte, current density, electrode area, and stability protocols continue to complicate cross-study comparisons.

Future studies should therefore prioritize standardized reporting and larger-area validation, including full-cell voltage–current-density curves, Faradaic efficiency, energy consumption, long-term durability, and, where relevant, dynamic operation. Scalable fabrication methods such as electrodeposition and direct growth are particularly attractive when they simultaneously provide good adhesion, controlled catalyst loading, and reproducible electrode architecture.

Taken together, practical Ni-based electrodes should be judged as integrated catalyst–electrode systems rather than isolated materials. The most useful evidence is obtained when catalyst composition and operating-state chemistry are linked to high-current performance, low cell voltage, durable electrode architecture, and reproducible fabrication.

Table 1: Comparison of representative nickel-based electrocatalysts for alkaline electrolysis under the conditions reported in the cited studies

Catalyst family	Representative evidence	Key activity data	Kinetic/structural evidence	Stability / practical relevance	Key references
Ni–Fe	NiFe-LDH-4 / NiFe-based electrodes	175 mV @ 10; 235 mV @ 50; 476.3 mV @ 500 mA cm^{-2} (OER)	Tafel 80.32 mV dec^{-1}; Cdl 0.149 mF cm^{-2}; Rct 0.454 Ω cm^2; XPS/TEM/EDS support reconstruction.	50 h at 500 mA cm^{-2}; AEM cell 1.725 V at 10 mA cm^{-2}. Strongest overall evidence, but condition dependent.	[10,66,68]
Ni–Co / Ni–Fe–Co	NiCo-LDH and multimetallic electrodes	303 mV @ 50 mA cm^{-2} (NiCo-LDH, OER)	Composition/phase effects require XRD, XPS, EIS, and ECSA/Cdl to separate intrinsic kinetics from surface-area effects.	Promising bifunctional behavior; matched-condition high-current and full-cell data remain less consistent.	[58]
Ni–Mo	NiMo-based alloy / coated electrodes	Quantitative value varies strongly with substrate and architecture;	Tafel, ECSA/Cdl, Rct, and post-test composition are needed to distinguish Mo effects from electrode architecture.	High-current operation is promising, but coating integrity and mass transport become limiting	[26,40,61]

Catalyst family	Representative evidence	Key activity data	Kinetic/structural evidence	Stability / practical relevance	Key references
		avoid single-value ranking.		near industrial rates.	
Ni sulfides/phosphides	Ni_2P/$NiCr(OH)_2$; NiFeS nanowires	111 mV @ 10 mA cm^{-2} HER; Rct 0.27 Ω cm^2 vs 0.53 Ω cm^2 for Ni_2P	Operando XPS/ATR-FTIR/Raman indicate interfacial electronic effects and reconstruction/oxidation.	Long-duration results exist, but reaction configuration must be distinguished from conventional overall water splitting.	[28,32]
Ni oxides/hydroxides/spinels	NiFe oxyhydroxides; Ni–Co / mixed-metal oxides	No single representative value; direct ranking is inappropriate without matched conditions.	XPS/XRD/TEM and operando methods are essential because active phases evolve under anodic bias.	Strong OER platform; remaining issues include Fe dissolution, reconstruction, and reproducibility of electrode architecture.	[66,68,69]

5. CONCLUSIONS

Nickel-based electrocatalysts provide a versatile platform for alkaline water electrolysis, with Ni–Fe systems showing particularly strong OER performance and Ni–Mo, sulfide, phosphide, oxide/hydroxide, heterostructured, MOF-derived, and multimetallic systems offering complementary routes for HER/OER improvement. Across the supplied literature, catalyst performance cannot be judged from overpotential alone because activity, reconstruction, accessible active sites, electrode architecture, bubble management, stability, and current density are closely coupled. The evidence therefore supports a catalyst–electrode–electrolyzer evaluation framework in which matched current density, kinetic descriptors, structural/operando characterization, Faradaic efficiency, full-cell voltage, and long-term durability are considered together. Future studies should prioritize standardized high-current testing, operating-state characterization, scalable electrode fabrication, reproducibility, and long-term full-cell validation.

REFERENCES

1. Vílchez-Cózar, Á., Colodrero, R., Marrero-López, D., Salcedo, I., Olivera-Pastor, P., & Cabeza, A. (2026). Isostructural ATMP-based phosphonates: A versatile platform for monometallic and Fe-doped Co/Ni electrocatalysts towards alkaline water electrolysis. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2026.155807
2. Asen, P., Jafarian, S., & Rakhtiyani, F. (2026). Montmorillonite decorated with 3D porous interwoven spiky NiCo-LDH as an advanced bifunctional electrocatalyst for boosting alkaline water electrolysis. Results in Engineering. https://doi.org/10.1016/j.rineng.2026.111130
3. Kharwar, Y., Nemala, S., Guha, P., Zaman, W., Yu, Z., Katam, S., ... Thalluri, S. (2026). Laser-directed approach for low-loading and highly efficient transition-metal-based high-entropy alloy anode for alkaline water electrolysis. Chemical Engineering Journal. https://doi.org/10.1016/j.cej.2026.177915
4. Dincer, I., & Agelin-Chaab, M. (2026). Comparative evaluation of Ni and Cu/Ni coated electrodes experimentally for alkaline electrolysis. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.152968
5. Wang, S., Geng, Z., Bi, S., Wang, Y., Gao, Z., Jin, L., & Zhang, C. (2024). Recent advances and prospects on Ni3S2-Based electrocatalysts for efficient alkaline water electrolysis. Green Energy & Environment. https://doi.org/10.1016/j.gee.2023.02.011
6. Roy, S., Moon, S., Patil, A., Seo, Y., Kang, K., & Chan Jun, S. (2025). Modulation of charge distribution of NiCo2S4 by inducing S vacancies and incorporating Ir single-atom and cluster catalyst for efficient alkaline water electrolysis. Materials Today Energy. https://doi.org/10.1016/j.mtener.2025.102086
7. Volanti, V., Zaffora, A., Iannucci, L., Grassini, S., Inico, E., Saetta, C., ... Santamaria, M. (2025). Design of Ni-coordinated MOF on stainless steel via electrodeposition as an efficient and stable oxygen evolution electrode for alkaline water electrolysis. Electrochimica Acta. https://doi.org/10.1016/j.electacta.2024.145416
8. Di Franco, F., Zaffora, A., Pupillo, D., Seminara, B., Pärnamäe, R., Tedesco, M., & Santamaria, M. (2024). Optimized base metals electrodeposition on Ni perforated plate type electrodes for high-performance alkaline water electrolysis. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2024.05.164
9. Jiang, W., Li, H., Yang, X., Chen, Y., & Eckert, K. (2026). Magnetic field-assisted jet electrodeposition of Ni–Co-based composite electrodes on nickel

foam for alkaline water electrolysis. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.152636

10. Li, X., Xu, S.-L., Li, J., Zhang, S.-S., Zhang, B.-Y., Zhao, R.-D., Zhao, D.-P., & Wu, F.-F. (2025). NiFe-LDH as a bifunctional electrocatalyst for efficient water and seawater electrolysis: Enhanced oxygen evolution and hydrogen evolution reactions. Nanoscale Advances, 7, 5546–5560. https://doi.org/10.1039/d5na00350d
11. Jiang, T., Poimenidis, I., Luo, D., Jiang, C., Zhao, Q., Bakker, R., ... Kyriakou, V. (2026). Synergistic effects of Ni^{3+}–Cu0/+ dual sites for efficient and stable hydrogen production in AEM water electrolysis. Applied Catalysis B: Environment and Energy. https://doi.org/10.1016/j.apcatb.2026.126597
12. Shetti, R., Shetti, S., Sreenivasulu, M., Alibrahim, K., Alodhayb, A., & Shetti, N. (2025). Microwave-assisted synthesis of Ni-doped carbon from bio-waste as a cost-effective electrocatalyst for effective and sustainable water electrolysis. Materials Today Sustainability. https://doi.org/10.1016/j.mtsust.2025.101236
13. Amorim, I., Spera, N., Nicoara, N., Ramasamy, D., Alves, D., Stollenwerk, M., ... Sousa, J. (2024). Overall alkaline water electrolysis over active, stable, low-loading iridium catalysts sputtered on nickel foam. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2024.10.306
14. Gultom, N., Sari, P., Silitonga, M., Ha, Q., & Kuo, D. (2026). Recent progress in nickel-based electrocatalysts for hydrogen evolution reaction by hydrothermal synthesis method in alkaline media: A comprehensive review. Applied Surface Science Advances. https://doi.org/10.1016/j.apsadv.2026.101023
15. Malaj, F., Lentini, D., Tampucci, A., Brogi, L., Cosenza, R., Berretti, E., ... Santoro, C. (2026). Green synthesis of $FeNi_3$/$FeNiO_x$ nanosponges via aluminum cementation for PGM-free anion exchange membrane water electrolysis. Electrochimica Acta. https://doi.org/10.1016/j.electacta.2026.148642
16. Huguet, D., Varela-Izquierdo, V., Cervera Martín, J., Chaudret, B., Soulantica, K., Sánchez, D., ... Godard, C. (2025). Revealing the Fe doping effect on Ni catalysts for low-alkalinity OER: from three-electrode systems to continuous flow anion exchange membrane water electrolyser. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.151868
17. Chen, D., Han, C., Sun, Q., Ding, J., Huang, Q., Li, T.-T., Hu, Y., Qian, J., & Huang, S. (2023). Bimetallic AgNi nanoparticles anchored onto MOF-derived nitrogen-doped carbon nanostrips for efficient hydrogen evolution. Green Energy & Environment, 8(1), 258–266. https://doi.org/10.1016/j.gee.2021.04.003
18. Shen, Z., Wang, S., Chen, J., *et al.,*(2022). An active $Zn_xNi_{1-x}S$@Mo_2C/carbon cloth electrode as an efficient catalyst for water electrolysis. Vacuum, 196, 110729. https://doi.org/10.1016/j.vacuum.2021.110729
19. Luo, F., Liu, W., Liu, Y., Yu, P., Jiang, X., & Chen, S. (2023). Rational modulation of interfacial electronic structure in Ni3S2/NiO p-n heterojunction for efficient alkaline oxygen evolution. Chemical Engineering Journal. https://doi.org/10.1016/j.cej.2023.146140
20. Xu, X., Guo, T., Xia, J., Zhao, B., Su, G., Wang, H., ... Toghan, A. (2021). Modulation of the crystalline/amorphous interface engineering on Ni-P-O-based catalysts for boosting urea electrolysis at large current densities. Chemical Engineering Journal. https://doi.org/10.1016/j.cej.2021.130514
21. Yao, D., Liu, C., Zhang, Y., Wang, S., Nie, Y., Qiao, M., & Zhu, D. (2025). Modulating selectivity and stability of direct seawater electrolysis for sustainable green hydrogen production. Materials Today Catalysis. https://doi.org/10.1016/j.mtcata.2025.100089
22. V, P., Mondal, P., Mukherjee, D., Laha, S., & Sarkar, S. (2026). Optimizing Ni/Co ratios in NiCo-LDH for enhanced hydrogen and oxygen evolution reactions in overall water splitting. Journal of Power Sources. https://doi.org/10.1016/j.jpowsour.2026.239607
23. Rafei, M., Hägglund, T., Dokhani, S., Lundblad, A., Wågberg, T., & Gracia-Espino, E. (2026). Fabrication of Nickel–Molybdenum-based Catalyst-Coated Substrates Using Precursor Solution Plasma Spraying: A Transferable Technique for High-Performance Anion Exchange Membrane Water Electrolyzers. ACS Applied Engineering Materials. https://doi.org/10.1021/acsaenm.6c00346
24. Liu, Y., Jiao, X., Chacón-Borrero, J., Martínez-Alanis, P., Xing, C., Wang, X., & Cabot, A. (2026). High-Entropy Phosphide CrMnFeCoNiP Nanosheets as Bifunctional Electrocatalysts for Anion-Exchange Membrane Seawater Electrolyzers. ACS Catalysis. https://doi.org/10.1021/acscatal.6c00083
25. Hnát, J., Ďurovič, M., Bystron, T., Strečková, M., & Bouzek, K. (2025). Electrodeposition as an attractive method of NiCoP cathode catalyst for alkaline membrane water electrolysis production. Chemical Engineering Journal Advances. https://doi.org/10.1016/j.ceja.2025.100837
26. Dias, E., Bhavanari, M., P T, A., Tangirala, V., Maddasani, S., & Tseng, C. (2026). Synergistic CoCO3/MnCO3/TiOx composite over nickel foam as anode for alkaline seawater electrolysis. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2026.154670
27. Chen, H., Alexiou, G., Vardalakis, F., Praisa, U., & Theodorus de Groot, M. (2025). Characterization of Raney Nickel electrodes for alkaline water electrolysis at high current densities. International

Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.150941
28. Jiang, F., Wu, Y., Zhuge, X., Wang, Y., Luo, K., & Liu, T. (2026). Duo-functional Ce-NiFe LDH/graphene oxide catalyst for high-performance water electrolysis. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2026.157023
29. Deng, L., Jin, L., Yang, L., Feng, C., Tao, A., Jia, X., ... Shi, J. (2025). Bubble evolution dynamics in alkaline water electrolysis. eScience. https://doi.org/10.1016/j.esci.2024.100353
30. Shin, H., Lee, J., Jang, D., Kim, Y., Jeong, H., & Kang, M. (2025). Enhanced oxygen evolution reaction and durability of carbon dot-anchored nickel-iron oxyhydroxide electrodes for alkaline water electrolysis at high current densities. Materials Today Advances. https://doi.org/10.1016/j.mtadv.2025.100560
31. Hoffmann, J., Gallenberger, J., Schmitt, N., Goerens, C., Dreizler, A., Hofmann, J., & Etzold, B. (2025). NiFeOOH deposition on various 3D electrode geometries to influence bubble dynamics under technical relevant alkaline water electrolysis conditions. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.03.298
32. Mirizzi, L., Muhyuddin, M., Lo Vecchio, C., Mosca, E., Baglio, V., Gatto, I., ... Santoro, C. (2025). Amorphous nanostructured Ni–Fe oxide as a notably active and low-cost oxygen evolution reaction electrocatalyst for anion exchange membrane water electrolysis. Industrial Chemistry & Materials. https://doi.org/10.1039/d5im00008d
33. Kuklewski, W., Akhtar, M., Komorowska, G., Cieślak, G., & Wejrzanowski, T. (2026). Multi–component Cr–Mn–Fe–Co–Ni oxide as bifunctional electrode for alkaline water splitting. Materials Letters: X. https://doi.org/10.1016/j.mlblux.2026.100274
34. Ji, X., Chen, X., Zhang, L., Meng, C., He, Y., Zhang, X., ... Yu, R. (2023). Anchoring nitrogen-doped Co2P nanoflakes on NiCo2O4 nanorod arrays over nickel foam as high-performance 3D electrode for alkaline hydrogen evolution. Green Energy & Environment. https://doi.org/10.1016/j.gee.2021.05.010
35. Zaffora, A., Volanti, V., Iannucci, L., Grassini, S., Valov, I., Saetta, C., ... Santamaria, M. (2026). Electrodeposited NiFe-succinate for the oxygen evolution reaction in anion exchange membrane water electrolysis. Fuel. https://doi.org/10.1016/j.fuel.2025.137329
36. Ji, X., Qi, H., Huang, S., Gao, P., Jin, T., Shi, Y., ... Zhang, J. (2026). Hydrogen-Spillover Catalysis Enabled by Ni Cluster Water-Activation Centers through Interfacial Electronic Modulation. ACS Catalysis. https://doi.org/10.1021/acscatal.6c03650
37. Ender, E., Wang, Y., Tseng, C., Taylor, H., Dwyer, L., Li, K., ... Walton, A. (2026). Surface Memory in Nickel HER Catalysts: Hydroxide Formation at Open-Circuit Potential. ACS Catalysis. https://doi.org/10.1021/acscatal.6c00325
38. Ansari, T., & Indra, A. (2026). The nickel age in electrocatalytic anodic reactions. JACS Au, 6(7), 3605–3623. https://doi.org/10.1021/jacsau.6c00252
39. Harnisch-Weidauer, L., de Brito Dorneles, E., Phalkun, N., Zhong, Q., Hao, Y., Hoang, T., ... Barecka, M. (2026). Metal Foam Morphology Affects the Run to Run Reproducibility of OER Using Nickel Catalysts. ACS Energy Letters. https://doi.org/10.1021/acsenergylett.6c00750
40. da Silva, G. C., Igel, C. S., & Cherevko, S. (2026). Setting the record straight: A systematic study on Fe and Ni dissolution in NiFe-based oxygen evolution reaction catalysts. ACS Catalysis, 16(9), 8633–8641. https://doi.org/10.1021/acscatal.6c01228
41. Jaramillo-Hernández, C., Seijas-Da Silva, A., Vert, V., Mizrahi, M., Leyva-Pérez, A., & Abellán, G. (2025). Fe Incorporation in Ni-Based Layered Hydroxides: Implications for Oxygen Evolution Electrocatalysis. Inorganic Chemistry. https://doi.org/10.1021/acs.inorgchem.5c02786
42. Geraci, S., Oliveri, R., Patella, B., Moukri, N., Pellitteri, F., Miceli, R., ... Inguanta, R. (2026). Thermally stabilized NiFeS nanowire electrodes for long-term alkaline oxygen evolution. Journal of Alloys and Compounds. https://doi.org/10.1016/j.jallcom.2026.189252
43. Jack Corbin, Cheng Lyu, David Trudgeon, Mikey Jones, Adeline Loh, Arthur Graf, Zhenyu Zhang, Jianyun Cao, Ida Nawrocka, Xiaohong Li; Systematic study of electrochemical performance of nickel iron hydroxide ($NiFe(OH)_2$) electrocatalyst at high current densities in alkaline seawater solutions. *RSC Sustainability* 2026; 4 (1): 493–510. https://doi.org/10.1039/d5su00650c
44. Mishra, A., Willoughby, J., Estes, S., Kohler, K., & Brinkman, K. (2024). Impact of morphology and oxygen vacancy content in Ni, Fe co-doped ceria for efficient electrocatalyst based water splitting. Nanoscale Advances. https://doi.org/10.1039/d4na00500g
45. Jiang, L., Jiang, L., Luo, X., Li, R., Zhou, Q., Wang, L., ... Mu, S. (2024). Iron-Induced vacancy and electronic regulation of nickle phosphides for ampere-level alkaline water/seawater splitting. Chemical Engineering Journal. https://doi.org/10.1016/j.cej.2024.157952
46. Yu, S., Cheng, I., Cheng, I., & Chen, J. (2026). NiMo sputter-deposition on tape-casted NiFe foam for anion exchange membrane water electrolysis. RSC Applied Interfaces. https://doi.org/10.1039/d5lf00358j
47. Jamal, T., Shafiullah, G. M., Dawood, F., Kaur, A., Arif, M. T., Pugazhendhi, R., Elavarasan, R. M., & Ahmed, S. F. (2023). Fuelling the future: An in-

depth review of recent trends, challenges and opportunities of hydrogen fuel cell for a sustainable hydrogen economy. Energy Reports, 10, 2103–2127. https://doi.org/10.1016/j.egyr.2023.09.011

48. Gómez-Sacedón, C., Rodríguez, V., Luque-Centeno, J., Martínez-Olaizola, M., González-Elipe, A., Yubero, F., ... Gil-Rostra, J. (2026). CoNiFe anodic catalysts prepared by magnetron sputtering deposition for anion exchange membrane water electrolysis. Journal of Power Sources. https://doi.org/10.1016/j.jpowsour.2026.240042
49. Han, B., Du, X., Li, J., Wang, H., Liu, G., & Li, J. (2022). Synergistic effect of Cu doping and NiPx/NiSey heterostructure construction for boosted water electrolysis. Applied Surface Science. https://doi.org/10.1016/j.apsusc.2022.154617
50. Rui, D., Li, J., Du, X., Liu, G., & Li, J. (2023). VFe@Ni/Ni3N Mott-Schottky heterojunction induced electronic modulation for efficient alkaline water splitting. Journal of Electroanalytical Chemistry. https://doi.org/10.1016/j.jelechem.2023.117763
51. Guo, D., Guo, X., Wen, L., & Xin, L. (2026). Synthetic coral-spherical Pd/CoNiP heterojunction catalyst with "rupture effect" for efficient alkaline hydrogen evolution reaction. Applied Catalysis B: Environment and Energy. https://doi.org/10.1016/j.apcatb.2025.125833
52. Abdelraouf, A., Abdelrahim, A., Abd El-Moghny, M., & El-Deab, M. (2025). Interface engineering: Enhancing the electrocatalytic activity of heterostructure NiFe-based alloy over valorized carbon waste towards water splitting. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2024.12.395
53. Khan, B., Zahra, S., Zhang, T., Rehman, A., Safdar, Z., Razzaq, A., ... Khan, A. (2026). Unraveling catalytic synergy in the MXene-derived NiFe-LDH composites for efficient OER and HER. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2026.156693
54. Malaj, F., Tampucci, A., Lentini, D., Brogi, L., Berretti, E., Coletti, C., ... Santoro, C. (2024). One-pot synthesis of FeNi3/FeNiOx nanoparticles for PGM-free anion exchange membrane water electrolysis. Electrochimica Acta. https://doi.org/10.1016/j.electacta.2024.145109
55. López-Fernández, E., Gómez-Sacedón, C., Gil-Rostra, J., Espinós, J., González-Elipe, A., Yubero, F., & de Lucas Consuegra, A. (2022). Nanostructured nickel based electrocatalysts for hybrid ethanol-water anion exchange membrane electrolysis. Journal of Environmental Chemical Engineering. https://doi.org/10.1016/j.jece.2022.107994
56. Bartoli, F., Castello, C., Peruzzolo, T., Berretti, E., Sediva, E., Bouzek, K., ... Miller, H. (2025). MoO3-xNiMoO4 nanorods synthesized using NiO nanoparticles for hydrogen evolution in anion exchange membrane water electrolysis. Chemical Engineering Journal. https://doi.org/10.1016/j.cej.2025.162026
57. Osorio, J., Quiroz, S., Cartagena, S., & Calderón, J. (2026). Realistic electrolyzer temperature and pressure conditions evaluation of NiFeP/Zn-coated electrodes for alkaline water splitting. Fuel. https://doi.org/10.1016/j.fuel.2025.136339
58. Carbone, S., Proietto, F., Bonafede, F., Oliveri, R., Patella, B., Ganci, F., ... Inguanta, R. (2023). Behavior of a forest of NiFe nanowires in KOH and NaCl solution for water electrolysis. Electrochimica Acta. https://doi.org/10.1016/j.electacta.2023.143120
59. Rodríguez, V., Gómez-Sacedón, C., Sánchez, P., & de Lucas-Consuegra, A. (2026). Anion exchange membrane electrolysis beyond the lab scale: a review on research and industry stacks. Current Opinion in Chemical Engineering. https://doi.org/10.1016/j.coche.2025.101218
60. Li, Y., Xie, X., Wang, Y., Yuan, X., & Li, F. (2023). Nickel-based alloy nanoparticles anchored on nickel mesh towards excellent and sustainable water electrolysis. International Journal of Electrochemical Science. https://doi.org/10.1016/j.ijoes.2023.100216
61. Frederiksen, M., Oglou, R., Lauritsen, J., Bentien, A., & Nielsen, L. (2024). Electrocatalytic and structural investigation of trimetallic NiFeMo bifunctional electrocatalyst for industrial alkaline water electrolysis. Electrochimica Acta. https://doi.org/10.1016/j.electacta.2024.143988
62. Saha, D., Tang, C., Khan, J., Jain, P., Yang, C., Dong, C., ... Watkins, J. (2026). Alkaline electrocatalytic water oxidation by Fe–Ni nanostructures on porous turbostratic carbon with tailorable metal–metal active sites. Chemical Science. https://doi.org/10.1039/d5sc05330g
63. Etzi Coller Pascuzzi, M., Man, A. J. W., Goryachev, A., Hofmann, J. P., & Hensen, E. J. M. (2020). Investigation of the stability of NiFe-(oxy)hydroxide anodes in alkaline water electrolysis under industrially relevant conditions. Catalysis Science & Technology, 10, 5593–5601. https://doi.org/10.1039/D0CY01179G
64. Omar, I., & Emran, K. (2026). Electrocatalytic oxygen evolution on Ni-modified Sr@TiO_2 nanotubes in alkaline medium. International Journal of Electrochemical Science. https://doi.org/10.1016/j.ijoes.2025.101271
65. Wang, X., Wang, T., Yu, Y., You, J., Hu, F., & Zhao, D. (2024). Enhancing the efficiency and stability of electrocatalysts for water splitting: NiCo-LDH nanosheet arrays at high current density. CrystEngComm, 26, 5144–5151. https://doi.org/10.1039/D4CE00564C
66. Zhang, J., Lv, X., Ren, T., Wang, Z., Bandosz, T., & Yuan, Z. (2022). Engineering heterostructured Ni@Ni(OH)2 core-shell nanomaterials for synergistically enhanced water electrolysis. Green

Energy & Environment. https://doi.org/10.1016/j.gee.2020.12.009

67. Tumiwa, J., & Mizik, T. (2025). Advancing nickel-based catalysts for enhanced hydrogen production: Innovations in electrolysis and catalyst design. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.02.020
68. Wang, X., Li, J., Zhu, X., Xu, Z., Xie, S., Chen, S., Wan, Y., Zhang, G., Ge, M., Zhang, W., Wang, C., & Li, R.-Q. (2026). Promoting effect of nickel-chromium hydroxide on nickel phosphide nanosheets for efficient hydrogen production coupled with sulfion degradation. Chemical Science, 17, 11954–11961. https://doi.org/10.1039/D6SC02309F
69. Park, S., Ji, S., Andrenacci, S., Lee, S., & Choi, Y. (2026). Toward Simplified Electrode Design: Development of Nickel-Efficient Catalytic NanoPTL for Sustainable AEM Water Electrolysis. ACS Nanoscience Au. https://doi.org/10.1021/acsnanoscienceau.5c00168
70. Twight, L., Osmieri, L., & Leonard, D. (2026). Activity Convergence between Continuous- and Pulsed-Deposition NiFe Hydroxide Anodes in Liquid Alkaline Electrolyzers. ACS Applied Materials & Interfaces. https://doi.org/10.1021/acsami.6c05938
71. Stavrou, M., Poimenidis, I., Klini, A., Farsari, M., Moustaizis, S., Konsolakis, M., & Loukakos, P. (2026). Unraveling the Contributions of Laser-Induced Ripples and Nanoparticles to Enhanced HER Performance of Nickel Electrodes. ACS Applied Materials & Interfaces. https://doi.org/10.1021/acsami.6c11963
72. Kroy, S., & Shin, W. (2024). Understanding the effect of electrode thicknesses on bubble detachment and Hydrogen Evolution Reaction (HER) in water electrolysis using bare nickel foam. Journal of Power Sources. https://doi.org/10.1016/j.jpowsour.2024.234820
73. Klaudia Maślana, Grzegorz Leniec, Karolina Pietrusewicz, Ewa Mijowska; Interfacial Engineering of Ni_2P with Iron and Carbon toward Enhanced Robustness and Charge Transfer in the Oxygen Evolution Reaction. *J. Phys. Chem. C* 30 April 2026; 130 (17): 6166–6179. https://doi.org/10.1021/acs.jpcc.6c01047
74. Doumbi, R., Neto, J., Morais, A., Freitas, A., Bohn, F., Furlan, K., ... Correa, M. (2025). Facile Sol–Gel Synthesis of Graphene-Supported FeNi Nanocatalysts for Enhanced Oxygen Evolution Reaction. ACS Omega. https://doi.org/10.1021/acsomega.5c07875
75. Ngo, Q. P., Paek, S. Y., Lee, J. Y., Nam, H. N., Phung, Q. M., Nguyen, T. H., Seo, J. Y., Yamauchi, Y., Sinh, L. H., Lee, Y. J., Kim, J. M., & Na, J. (2026). Tailored Design of Iridium Single Atoms on Mn–Ni-Phytate with Robust Bifunctionality for Enhanced Anion Exchange Membrane Water Electrolysis. Advanced Energy Materials, 16, e06645. https://doi.org/10.1002/aenm.202506645
76. Han, Y., Wang, J., Liu, Y., Li, T., Wang, T., Li, X., Ye, X., Li, G., Li, J., Hu, W., & Deng, Y. (2024). Stability Challenges and Opportunities of NiFe-Based Electrocatalysts for Oxygen Evolution Reaction in Alkaline Media. Carbon Neutralization, 3, 172–198. https://doi.org/10.1002/cnl2.110
77. Kumari, E. P., Kumar, A., Tarlochan, F., & Al-Marri, M. J. (2025). Impact of Electrolyte Temperature on Solution-Combustion Synthesized NiO/Ni Nanoparticles as Oxygen Evolution Reaction Electrocatalyst. ChemistryOpen, 15, e202500137. https://doi.org/10.1002/open.202500137
78. Lee, H., Mai, T. T., Jeong, W., Kim, J. Y., Park, Y., Hwang, Y. J., An, B., Lee, Y., Kim, G., Jeong, H., Ahn, Y., Kim, C., Wang, D. H., Jang, S., & Ha, D.-H. (2026). Ni–P Nanoarray Scaffolds That Elevate Self-Supported Phosphides and Commercial Catalysts for Alkaline and Anion-Exchange-Membrane Water Electrolysis. Small, 22, e74129. https://doi.org/10.1002/smll.74129
79. Muhammad, A., Rodriguez-Flores, T., Muhyuddin, M., Di Fonzo, F., Berretti, E., Lavacchi, A., Lo Vecchio, C., Gatto, I., & Baglio, V. (2026). Impact of Crystallinity and Ni–Fe Composition on the Oxygen Evolution Performance of $Ni_xFe_{1-x}O$ Electrocatalysts in Anion Exchange Membrane Water Electrolysis. ChemSusChem, 19, e202502755. https://doi.org/10.1002/cssc.202502755
80. Yu, Z., Bai, Y., Tsekouras, G., & Cheng, Z. (2022). Recent Advances in Ni-Fe (Oxy)hydroxide Electrocatalysts for the Oxygen Evolution Reaction in Alkaline Electrolyte Targeting Industrial Applications. Nano Select, 3, 766–791. https://doi.org/10.1002/nano.202100286
81. Wu, K., Lyu, C., Cheng, J., Ding, W., Wu, J., Wang, Q., Lau, W.-M., & Zheng, J. (2024). Defect Engineering in Transition-Metal (Fe, Co, and Ni)-Based Electrocatalysts for Water Splitting. Carbon Energy. https://doi.org/10.1002/cey2.485
82. Antony, R. P., Zerdoumi, R., Saddeler, S., Krysiak, O. A., Banko, L., Ludwig, A., & Schuhmann, W. (2024). High-Throughput Screening of Co-Fe-Ni Electrocatalysts for High-Current-Density Water Electrolysis. ChemCatChem. https://doi.org/10.1002/cctc.202401749
83. Heath, M. M., Poureshghi, F., Seland, F., Sunde, S., & Kriek, R. J. (2023). The Enhancing Effect of α–FeOOH on Ni Surfaces Toward Electrolytic Water Splitting. Energy Technology, 11, 2300313. https://doi.org/10.1002/ente.202300313
84. Yu, M., Budiyanto, E., & Tüysüz, H. (2022). Principles of Water Electrolysis and Recent Progress in Cobalt-, Nickel-, and Iron-Based Oxides for the Oxygen Evolution Reaction. Angewandte Chemie International Edition, 61, e202103824. https://doi.org/10.1002/anie.202103824

85. Sim, J., Kim, W. S., Kim, J., Tamboli, A. M., Jung, Y., Im, S., Oh, J. S., Kim, J. K., Kim, B.-H., & Kim, C.-H. (2026). Facilitating Hydrogen Evolution Reaction Activity in Alkaline Water Electrolysis via Formation of Ni-Co_2P Heterojunction. Energy & Environmental Materials. https://doi.org/10.1002/eem2.70385
86. Zhang, X., Wang, J., Zong, K., Chen, Z., Yang, X., Yang, L., Wang, X., & Chen, Z. (2025). Recent Advances in Non-Noble Metal-Based Electrocatalysts for Hybrid Water Electrolysis Systems. Carbon Energy, 7, e679. https://doi.org/10.1002/cey2.679
87. Wang, Y., Feliciano, G. T., Kumar, A., Auer, A. A., & Tüysüz, H. (2025). Experimental and Theoretical Insights into the Role of Iron in the Rapidly Fabricated Ni/Fe Electrodes for the Oxygen Evolution Reaction. ChemSusChem, 18, e202500281. https://doi.org/10.1002/cssc.202500281
88. Tang, H., Cui, C., & Wang, J. (2026). Design Principles of Electrocatalysts for Industrial-Scale Water Electrolysis. Advanced Energy Materials. https://doi.org/10.1002/aenm.71379
89. Li, Y., Lin, X., Yang, Y., Georgiadou, S., Du, B., Qi, Z., Saremi-Yarahmadi, S., & Lin, W.-F. (2025). Engineering Low-Cost NiFeMo Bifunctional Catalyst into High-Performance Superaerophobic Nanoarray Electrode for Water and Seawater Electrolysis at Industrial-Scale Current Density. ChemCatChem, 17, e01040. https://doi.org/10.1002/cctc.202501040
90. Guo, K., Wang, T., Kunimoto, M., & Homma, T. (2026). Unveiling Anodic Reconstruction of Electroless-Deposited Dual-Sided NiFeP Catalyst-Coated Membranes for Efficient Anion Exchange Membrane Water Electrolysis. Energy & Environmental Materials. https://doi.org/10.1002/eem2.70324
91. Hegazy, M. B. Z., Zander, J., Weiss, M., Simon, C., Gerschel, P., Sanden, S. A., Smialkowski, M., Tetzlaff, D., & Kull, T. (2024). $FeNi_2S_4$—A Potent Bifunctional Efficient Electrocatalyst for the Overall Electrochemical Water Splitting in Alkaline Electrolyte. Small. https://doi.org/10.1002/smll.202311627
92. Kitiphatpiboon, N., Chen, M., Feng, C., Li, S., Abudula, A., & Guan, G. (2024). Highly Efficient Electrocatalysts for Seawater Electrolysis under High Current Density: A Critical Review. MetalMat, 1. https://doi.org/10.1002/metm.11
93. Peng, L., Wang, C., Wang, Q., Shi, R., Zhang, T., & Waterhouse, G. I. N. (2021). Rationally Designed Ni–Ni_3S_2 Interfaces for Efficient Overall Water Electrolysis. Advanced Energy and Sustainability Research. https://doi.org/10.1002/aesr.202100078
94. Khalid, M., Barnabé, S., & Shahgaldi, S. (2026). Coral-Reef-Like Nanoporous Nickel Architecture for Enhanced Oxygen/Hydrogen Evolution Reaction and Alkaline Water Electrolysis. Advanced Sustainable Systems, 10, e70556. https://doi.org/10.1002/adsu.70556
95. Rao, N. N., Kumar, A. A., Kúš, P., Alex, C., Naduvil Kovilakath, M. S., Hrbek, T., Matolínová, I., & John, N. S. (2025). Accelerated Electro-Conversion of a Nickel Coordination Complex for Hybrid Water Electrolysis. Small, 21, e07907. https://doi.org/10.1002/smll.202507907
96. Metaxa, M. S., Vamvasakis, I., & Armatas, G. S. (2026). Heterointerface Engineering of FeOOH@Ni_3N Electrocatalysts for Industrially Compatible Alkaline Water Electrolysis. Small, 22, e13136. https://doi.org/10.1002/smll.202513136
97. Lee, G., Jun, S. E., Lim, J., Kim, J., Lee, H., Cheon, W. S., Ryoo, G. W., Cho, B.-G., Lee, S., Kwon, M. S., Park, I.-H., & Jang, H. W. (2025). Tuning Hydrogen Binding on Ru Sites by Ni Alloying on MoO_2 Enables Efficient Alkaline Hydrogen Evolution for Anion Exchange Membrane Water Electrolysis. Advanced Science, 12, 202414622. https://doi.org/10.1002/advs.202414622
98. Jeong, Y., Begildayeva, T., Theerthagiri, J., Min, A., Moon, C. J., Kim, J., Naik, S. S., & Choi, M. Y. (2024). Laser-Driven Liquid Assembly: Metal-Nanocluster-Decorated $Ni(OH)_2$/Nickel Foam for Efficient Water Electrolysis. SmartMat, 5, e1281. https://doi.org/10.1002/smm2.1281
99. Tourneur, J., Lagrost, C., & Fabre, B. (2023). Robust and Bifunctional Electrodeposited NiCoCr Ternary Alloy for Alkaline Water Electrolysis. Advanced Energy and Sustainability Research. https://doi.org/10.1002/aesr.202300133
100. Ruck, S., Hutzler, A., Thiele, S., & van Pham, C. (2024). Highly Active NiRu/C Cathode Catalyst Synthesized by Displacement Reaction for Anion Exchange Membrane Water Electrolysis. Small Methods, 9, e2401179. https://doi.org/10.1002/smtd.202401179
101. Zhu, X., Yao, X., Lang, X., Liu, J., Singh, C.-V., Song, E., Zhu, Y., & Jiang, Q. (2023). Charge Self-Regulation of Metallic Heterostructure Ni_2P@Co_9S_8 for Alkaline Water Electrolysis with Ultralow Overpotential at Large Current Density. Advanced Science, 10, 2303682. https://doi.org/10.1002/advs.202303682
102. Zaffora, A., Di Franco, F., Pupillo, D., Seminara, B., Tranchida, G., & Santamaria, M. (2023). Highly Active and Stable NiCuMo Electrocatalyst Supported on 304 Stainless Steel Porous Transport Layer for Hydrogen Evolution in Alkaline Water Electrolyzer. Advanced Sustainable Systems, 7, 2200486. https://doi.org/10.1002/adsu.202200486

