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论文题目： Dual-Anion Electrolyte Engineering for Stable
Seawater Oxidation

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摘要: Alkaline seawater electrolysis represents a promising approach for large-scale green hydrogen production, leveraging abundant seawater feedstock. Nevertheless, its practical implementation faces severe challenges including chloride-induced corrosion, competitive parasitic oxidation, and transition-metal dissolution during the oxygen evolution reaction (OER). In this work, we propose a straightforward dual-anion electrolyte-engineering strategy by combining F^- and B(OH)_4^- to enhance seawater-oxidation stability. Benefiting from this dual-anion-assisted electrolyte, the FeNi-layered double hydroxides supported on nickel foam (FeNi-LDH/NF) maintains favorable OER activity and achieves stable operation for over 1500 h at 1 A cm^{-2} . By contrast, the blank electrode without anion additives fails after approximately 600 h. Comprehensive characterizations including XPS, operando Raman spectroscopy, metal-dissolution measurements, Bode impedance analysis, and molecular-dynamics simulations reveal the intrinsic synergy between F^- and B(OH)_4^- . Such synergistic effect suppresses near-surface Cl^- accumulation and mitigates Ni/Fe dissolution. This work highlights that electrolyte engineering via F^- - B(OH)_4^- dual-anion synergy serves as an effective strategy for constructing durable alkaline seawater-electrolysis systems.

关键词: NiFe-LDH; seawater electrolysis; oxygen evolution reaction; chloride corrosion; F^- - B(OH)_4^- complex

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论文正文:

1. Introduction

Hydrogen is widely recognized as a crucial energy carrier for a future low-carbon energy system due to its ability to store electricity in chemical form and its lack of carbon dioxide emissions when used directly as a fuel [1-3]. In response to the scarcity of freshwater resources, direct seawater electrolysis has emerged as an appealing method to minimize freshwater consumption [4-6]. However, the chemically complex composition of seawater imposes significantly harsher operating conditions compared to freshwater systems [7]. Chloride-induced degradation at the anode remains a critical bottleneck for the practical implementation of seawater electrolysis. Under positive anodic potentials, Cl⁻ ions can accumulate near the electrode, penetrate porous catalyst layers, and facilitate the formation of soluble metal-chloride species, thereby accelerating the dissolution of transition metals [8, 9]. NiFe layered double hydroxides (NiFe-LDH) are among the most effective non-noble-metal catalysts for oxygen evolution reaction (OER) in alkaline media [2, 10]. However, their practical application in alkaline seawater electrolysis is hindered by the combined effects of chloride attack and anodic oxidation, which destabilize the reconstructed active phases and accelerate the dissolution of Ni/Fe during prolonged anodic operation [11, 12]. Therefore, it is necessary to enhance the resistance of FeNi-LDH to chloride attack and oxidation.

Strategies include constructing protective catalyst layers or introducing functional anions into the electrode interface [13-15]. For example, sulfate-assisted NiFe/NiS_x and Ni₃S₄/NiFe-LDH utilize the in-situ oxidation of sulfur species into sulfate anions during operation, creating an anion-rich interface that repels Cl⁻ and mitigates catalyst corrosion [12, 16]. Similarly, oxidation-derived or released species, such as Fe(CN)₆³⁻ and PO₄³⁻ from CoFePBA/Co₂P [17] and Al(OH)_n⁻ from CoFeAl-LDH [18], regulate local ion distributions and suppress chloride-induced degradation during operation. Phosphate additives have been shown to facilitate Cl⁻ exclusion, OH⁻ transport, and local alkalinity through the interconversion of PO₄³⁻/HPO₄²⁻ [19]. Additionally, PF₆⁻ has also been demonstrated to stabilize LDH interfaces through surface adsorption,

effectively shifting interfacial Cl^- away from the electrode and suppressing Fe segregation and dissolution [20]. Nevertheless, the relatively complex design of electrodes hinders large-scale application, and chloride-induced metal dissolution is governed by several coupled interfacial processes, a single additive rarely satisfies all relevant requirements.

In this study, we propose the dual-anion (F^- and B(OH)_4^-) electrolyte strategy for enhancing the seawater oxidation stability of NiFe-LDH. In detail, F^- as a small ion with strong hydration ability can strongly interact with surrounding water molecules and B(OH)_4^- contains several hydroxyl groups and can interact with water and NiFe-based oxyhydroxide surfaces. The introduced F^- and B(OH)_4^- not only repels Cl^- to enhance corrosion resistance, but also suppresses transition-metal dissolution. As a result, FeNi-LDH/NF can stably electrolyze seawater for 1500 hours at 1 A cm^{-2} in a F^- and B(OH)_4^- -assisted electrolyte, significantly longer than in without additive electrolyte (600 h). This work highlights the impact of electrolyte regulation on the stability of electrocatalysis.

2. Methodology

2.1 Chemicals and materials:

$\text{Ni(NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and $\text{Fe(NO}_3)_3 \cdot 9\text{H}_2\text{O}$ were purchased from Aladdin Industrial Co. Urea, KOH, and NaCl were purchased from Beijing Chemical Reagents Co. KF and H_3BO_3 were purchased from Shanghai Macklin Biochemical Co. Deionized water with a resistivity of $\geq 18 \text{ M}\Omega$ was utilized for preparation of all aqueous solutions. All reagents were of analytical grade and were employed directly without further purification. In strongly alkaline solutions, H_3BO_3 undergoes deprotonation, resulting in B(OH)_4^- as the predominant borate species.

2.2 Synthesis of NiFe-LDH:

0.66 mmol $\text{Ni(NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 0.33 mmol $\text{Fe(NO}_3)_3 \cdot 9\text{H}_2\text{O}$, and 5 mmol urea were dissolved in 35 mL deionized water. Nickel foam was subjected to ultrasonic cleaning in 3 M HCl for 5-10 minutes, followed by thorough rinsing with ethanol and deionized water. Subsequently, this solution and a piece of cleaned Ni foam measuring $2 \times 4 \text{ cm}^2$

were transferred into a Teflon-lined stainless steel autoclave and maintained at 120°C for 12 hours to synthesize the NiFe LDHs electrode.

2.3 Physical characterization:

XRD patterns were recorded on an Ultima IV (Rigaku) in the range from 5° to 90° at a scan rate of 5°/min. SEM images were obtained on a Zeiss SUPRA55 scanning electron microscope, operated at 10 kV. XPS was performed by using a K-Alpha model (Thermo Scientific). ICP-OES was carried out on the Thermo Fisher iCAP 7400.

2.4 Electrochemical Measurements:

A three-electrode system was employed to conduct all electrochemical measurements at a temperature of 25 °C. The electrocatalyst, with a working electrode surface area of 1 cm × 1 cm, utilized a Hg/HgO reference electrode and a graphite rod as the counter electrode. The measured potential versus Hg/HgO could be converted to the potential versus reversible hydrogen electrode (RHE) by Equation (1):

$$E_{\text{RHE}} = E_{\text{Hg/HgO}} + 0.098 + 0.059 \times \text{pH} \quad (1)$$

OER performance was evaluated in alkaline simulated seawater with (1 M KOH + 0.5 M NaCl) or without added halide ions (1 M KOH + 0.5 M NaCl + X⁻). The electrochemical behavior was investigated using reverse linear sweep voltammetry (LSV) from 1 to 0 V vs Hg/HgO at a scan rate of 5 mV s⁻¹. The curves were manually corrected with 90% iR compensation. The R is obtained from electrochemical impedance spectroscopy (EIS), with the frequency range of 10⁵ to 10⁻¹ Hz and an amplitude of 10 mV. Tafel slopes were derived by plotting potential against log(j) from the LSV curves.

The corrosion behavior was evaluated across various electrolytes using a conventional three-electrode system on an electrochemical workstation (CS2350H, Wuhan Corrtest Instruments). A piece of Ni foam (NF) with an exposed area of 1 × 1 cm² served as the working electrode, a platinum wire as the counter electrode, and a mercury/mercury oxide (Hg/HgO) electrode as the reference. The system could stabilize at the open-circuit potential until the potential drift was less than 1 mV/min. Polarization curves were then recorded from -0.3 V to 0.5 V versus the open-circuit

potential at a scan rate of 0.5 mV s^{-1} to determine the corrosion potential (E_{corr}) and corrosion current density (i_{corr}).

2.5 In-situ electrochemical Raman measurements:

Electrochemical Raman spectroscopy was carried out on a Horiba Lab RAM HR Evolution confocal Raman spectrometer equipped with a 532 nm laser source and a $50\times$ objective lens, with an acquisition time of 90 seconds. The electrochemical workstation (CHI 660D, Chenhua, Shanghai) was used to perform the Amperometric i-t Test under OCP to 1.49V vs RHE. Each spectrum was obtained at least three times with an exposure time of 90 seconds.

2.6 Molecular dynamic (MD) simulations:

To simulate the distribution of OH^- and Cl^- on the electrode surface in various electrolytes, two models were constructed, representing simulated seawater and simulated seawater with an additional 1.5 M F^- , respectively, applied to the surface of a NiFe-LDH electrode model. Both electrolyte models contained 500 H_2O molecules, 5 Na^+ , 5 Cl^- , 10 K^+ , and 10 OH^- ions, while the F-containing model additionally included 15 K^+ and 15 F^- ions, and $\text{F}^- + \text{B}(\text{OH})_4^-$ -containing model additionally included 4 $\text{B}(\text{OH})_4^-$ and 6 OH^- . A vacuum layer approximately $30 \text{ \AA}$ was added above the solution to eliminate interactions between periodic images, resulting in a simulation box of approximately $36 \text{ \AA} \times 32 \text{ \AA} \times 60 \text{ \AA}$. All atoms in the electrode model were fixed, while all particles in the solution were allowed to move freely. Periodic boundary conditions were applied along the x and y directions. Packmol was used to build the initial configurations of the model systems. The COMPASS III force field was used for molecular simulations. The Nosé–Hoover thermostat was applied to maintain constant NVT conditions with a relaxation time of 0.1 ps and a temperature of 300 K. The velocity Verlet algorithm with a time step of 1.0 fs was used to integrate the equations of motion. A cutoff distance of $20 \text{ \AA}$ was applied to all non-bonded interactions. All reported results were averaged over a 1000 ps simulation, with atomic coordinates and charges collected every 1.0 ps for post-analysis.

3. Results and Discussion

FeNi-LDH array was fabricated on nickel foam (FeNi LDH/NF) by a simple solvothermal method by using $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ and $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ as metallic precursors, urea as the reductant (Figure 1a). The crystal structure of FeNi-LDH/NF was characterized by the X-ray diffraction (XRD) pattern. Noting that the strong diffraction signals of nickel foam were removed to avoid the interference. The XRD pattern shows the characteristic reflections of NiFe-LDH. The strong peaks assigned to the (003) and (006) planes appear at approximately 11° and 23° , respectively, and additional reflections such as (012), (015), (018), and (113) are also visible. These peaks agree with the standard NiFe-LDH pattern (PDF#40-0215), confirming the expected layered structure[23]. The morphology of the FeNi-LDH/NF was also analyzed by scanning electron microscopy (Figure 1c). NiFe-LDH/NF exhibits a network of interwoven nanosheets, which are supported by a multidimensional porous nickel-foam substrate, with each nanosheet having a lateral size of less than 200 nm. This nanoscale architecture facilitates the complete exposure of catalytic active sites and enhances the interaction between electrode and electrolyte. Furthermore, energy dispersive X-ray spectroscopy (EDS) elemental mapping confirmed the uniform distribution of Ni, Fe, and O throughout the NiFe-LDH (Figure 1d).

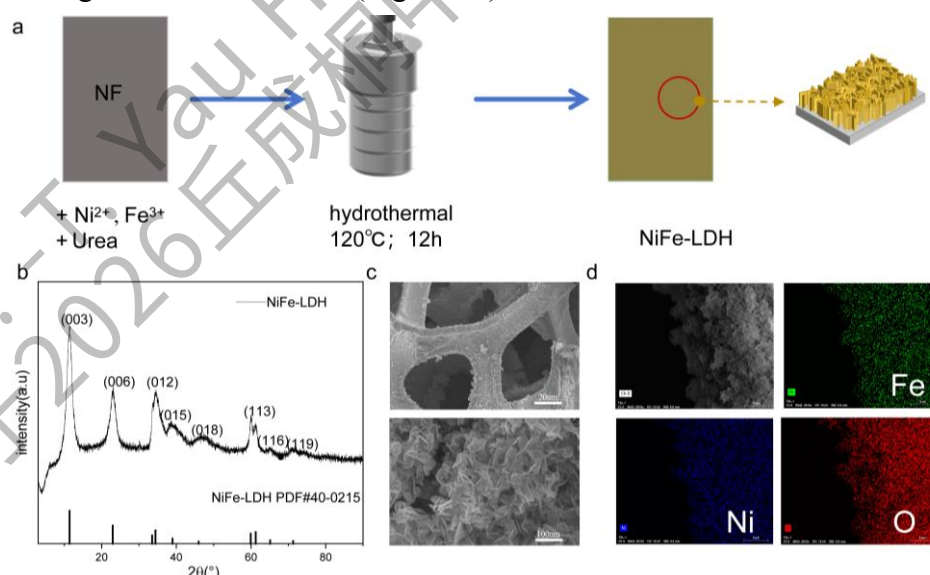


Figure 1. (a) Schematic route for the synthesis of NiFe-LDH. (b) XRD pattern, (c) SEM image, and (d) EDS elemental mapping of NiFe-LDH.

To evaluate the individual and synergistic effects of F^- and $\text{B}(\text{OH})_4^-$ additives on

the OER behavior of NiFe-LDH, cyclic voltammetry (CV) measurements were systematically performed in alkaline simulated seawater electrolytes containing different concentrations of coupled anion additives, the overpotential values extracted at 10 mA cm^{-2} from all CV curves were summarized into a two-dimensional activity map (Figure 2a). A low-overpotential region appears at relatively high (1.5–1.6 M) F^- concentrations of about 1.5 combined with moderate B(OH)_4^- concentrations of about 0.1–0.4 M, indicating an optimal electrochemical activity window for the $\text{F}^- + \text{B(OH)}_4^-$ synergistic electrolyte regulation. The effect of electrolyte composition on the stability of NiFe-LDH was further evaluated at 500 mA cm^{-2} in a more corrosive and higher salty electrolyte containing 1 M KOH and 2 M NaCl (Figure 2b). Among these candidates, the electrolyte containing 1.5 M F^- and 0.4 M B(OH)_4^- helps NiFe-LDH to exhibit the most stable operation, identifying this composition as the optimized electrolyte for subsequent mechanistic investigations and device-level evaluation. For comparison, blank (1 M KOH + 0.5 M NaCl), F^- (1 M KOH + 0.5 M NaCl + 1.5 M F^-), B(OH)_4^- (1 M KOH + 0.5 M NaCl + 0.4 M B(OH)_4^-), $\text{F}^- + \text{B(OH)}_4^-$ (1 M KOH + 0.5 M NaCl + 1.5 M F^- + 0.4 M B(OH)_4^-) were investigated to distinguish the contributions of anions coupled effects. In Figure 2c, NiFe-LDH required an overpotential of approximately 234 mV to reach 10 mA cm^{-2} in the blank electrolyte. The addition of F^- significantly improved the OER activity, decreasing η_{10} to approximately 223 mV, whereas B(OH)_4^- alone showed a similar activity to the blank electrolyte with an η_{10} of approximately 233 mV. When F^- and B(OH)_4^- were combined, a low η_{10} of approximately 225 mV was maintained, demonstrating that the dual-anion electrolyte preserves favorable OER activity. All polarization curves were iR-corrected using the solution resistance determined by electrochemical impedance spectroscopy (EIS), excluding changes in solution resistance as the main origin of the observed activity differences. Corrosion polarization measurements further revealed the influence of the electrolyte additives on the corrosion behavior of NiFe-LDH (Figure 2d). The corrosion potential (E_{corr}) progressively shifted from 0.867 V in the blank electrolyte to 0.909 V with F^- , 0.921 V with B(OH)_4^- , and 0.975 V in the $\text{F}^- + \text{B(OH)}_4^-$ electrolyte. The dual-anion system therefore exhibited the most positive corrosion potential, suggesting an improved corrosion-resistant interfacial environment. Together, these results indicate

that F^- mainly contributes to the improvement in OER activity, while the combination of F^- and $\text{B}(\text{OH})_4^-$ provides a favorable balance between catalytic activity and corrosion resistance. This enhanced durability was further confirmed by chronopotentiometry at 1 A cm^{-2} in $1 \text{ M KOH} + 0.5 \text{ M NaCl}$ (Figure 2e). The additive-free electrode failed after $\sim 600 \text{ h}$ due to a rapid potential increase, whereas the optimized $\text{F}^- + \text{B}(\text{OH})_4^-$ electrolyte enabled stable operation for over 1500 h with only minor potential fluctuations. Thus, these results show that the optimized $\text{F}^- + \text{B}(\text{OH})_4^-$ electrolyte significantly improves the corrosion resistance and high-current durability of NiFe-LDH.

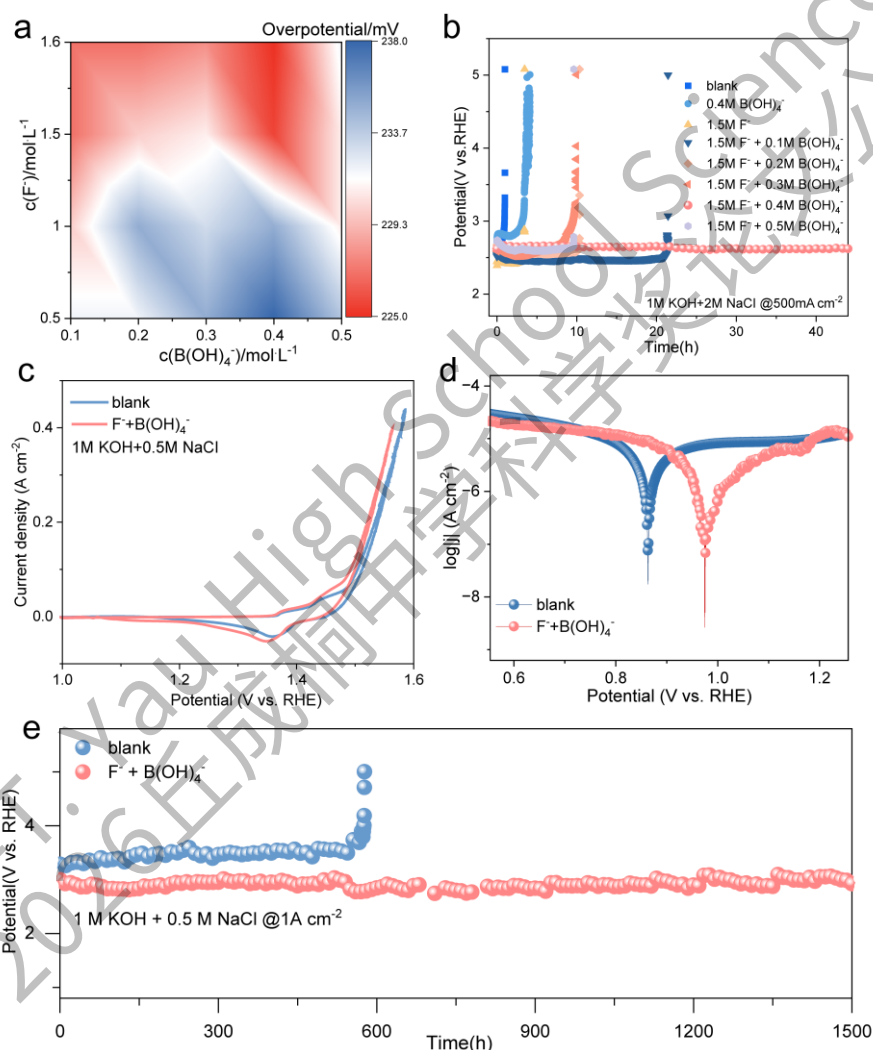


Figure 2. (a) Two-dimensional overpotential map at 10 mA cm^{-2} as a function of F^- and $\text{B}(\text{OH})_4^-$ concentrations; the red region represents lower overpotential. (b) Chronopotentiometry (CP) tests at 500 mA cm^{-2} in $1 \text{ M KOH} + 2 \text{ M NaCl}$ at different $\text{F}^- + \text{B}(\text{OH})_4^-$ compositions. (c) Polarization curves of NiFe-LDH with/without $\text{F}^- + \text{B}(\text{OH})_4^-$ (d) corrosion polarization curves. (e) Chronopotentiometry (CP) tests at 1 A cm^{-2} for NiFe-LDH in $1 \text{ M KOH} + 0.5 \text{ M NaCl}$.

To investigate the origin mechanism of the enhanced seawater oxidation durability by the assistant with FB, we performed x-ray photoelectron spectroscopy (XPS) to probe the surface chemical environments of Ni and Fe before and after operation in different electrolytes. As shown in Figure 3a, following a 24-hours chronopotentiometric test at 400 mA cm^{-2} , the Fe 2p peak of NiFe-LDH operated in FB-containing electrolytes shifted toward higher binding energies by approximately 0.28 eV relative to that observed in the FB-free electrolyte [25], which can be attributed to the surface interaction with F^- and B(OH)_4^- . In contrast, only negligible changes ($\leq 0.04 \text{ eV}$) were observed for the Ni 2p peaks after operation in FB-free and FB-containing electrolyte (Figure 3b) [26, 27], indicates that the FB-electrolyte predominantly modifies the surface chemical environment of Fe and no effect the chemical environment of Ni. Meanwhile, F-and B related signal clearly appeared after operation in the FB-containing electrolyte, further confirming the interaction between Fe with F^- and B(OH)_4^- (Figure 3c). Furthermore, operando Raman spectroscopy observes borate-related B–O vibration, suggests the presence of borate species at the catalyst/electrolyte interface (Figure 3d) [28].

The influence of electrolyte composition on the dissolution of metal during seawater oxidation was evaluated by inductively coupled plasma optical emission spectroscopy (ICP-OES). As shown in Figure 4d, the dissolved Ni amount from the NiFe LDH/NF in FB-containing electrolyte is 0.15 mg, which is significantly lower than that in the FB-free seawater (1.24 mg). Similarly, the dissolved Fe amount in FB-containing seawater is also lower than in FB-free electrolyte (Figure 3e). These results demonstrated that their combination suppresses transition-metal dissolution, which provides sustained stabilization during prolonged electrolysis.

Operando Bode analysis was further employed to examine the interfacial electrochemical behavior of NiFe-LDH in both the FB-free (**Figure 4a**) and FB-containing electrolytes (**Figure 4b**). As the applied potential increased, the phase angle in the low- and intermediate-frequency regions gradually decreased in both systems. Notably, in comparison to the FB-free electrolyte, the phase angle in the FB-containing electrolyte decreased more rapidly, indicating enhanced interfacial electrochemical processes and more favorable OER kinetics. Furthermore, a significant difference was

observed in the high-frequency region, where FB-containing electrolyte displayed a considerably larger phase angle above approximately 10^4 Hz, suggesting an enhanced capacitive response at the catalyst-electrolyte interface [29]. These results demonstrate that the dual-anion electrolyte not only accelerates the interfacial processes related to OER but also modifies the interfacial electrochemical behavior of NiFe-LDH.

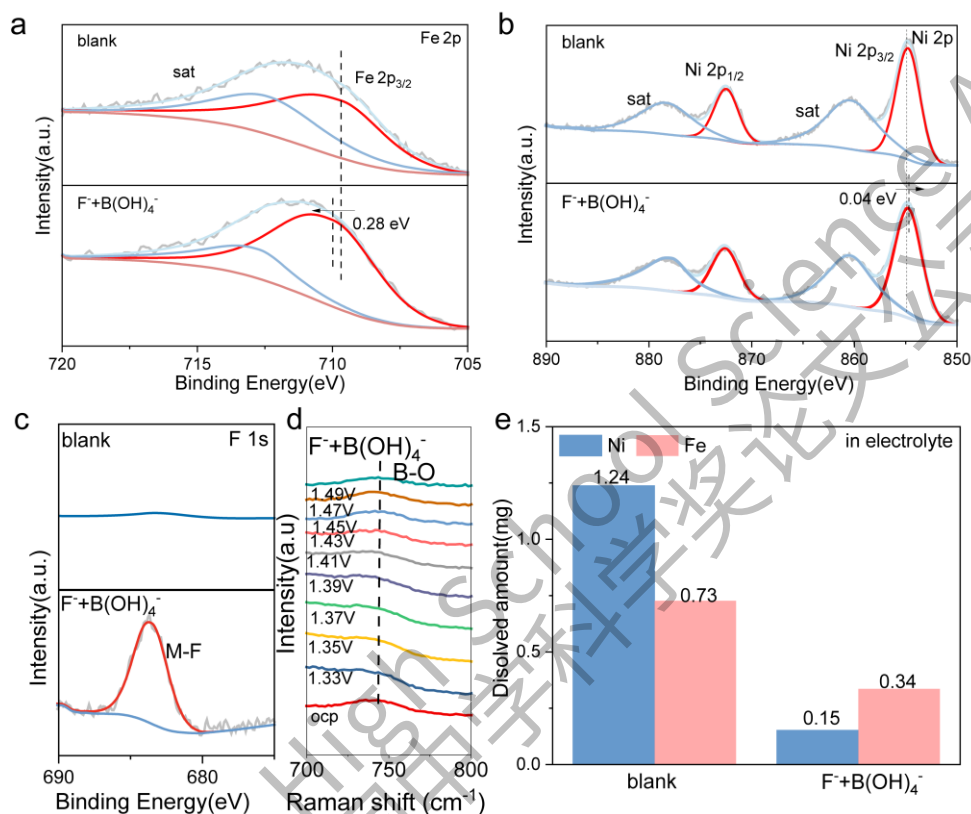


Figure 3. (a) Fe 2p XPS, (b) Ni 2p XPS, and (c) F 1s XPS of NiFe-LDH post CP test in blank and F+B(OH)₄⁻ electrolytes. (d) In situ Raman of NiFe-LDH in F+B(OH)₄⁻ (e) The dissolved amount of Ni and Fe after the Chronopotentiometry (CP) 24h test in blank and F+B(OH)₄⁻ electrolytes.

MD simulations provide a more direct molecular picture (Figure 4c). The representative configuration in Figure 4 contains the NiFe-LDH surface, water, F⁻, B(OH)₄⁻, and Cl⁻. The differentiated distributions of F⁻ and B(OH)₄⁻ markedly alter the interfacial distribution of Cl⁻. As shown by the Cl⁻ radial distribution functions in 0.5M NaCl (Figure 4d), chloride begins to appear at approximately 2.0 Å from the NiFe-LDH surface in the blank electrolytes, whereas this onset shifts outward to about 5 Å in the F+B(OH)₄⁻ electrolytes. This pronounced reduction confirms that the dual-anion electrolyte effectively suppresses chloride access to the catalyst surface.

Based on these results, a possible cooperative protection mechanism is proposed. B(OH)_4^- contains multiple hydroxyl groups and can interact with the hydroxyl-rich NiFe-LDH surface and surrounding water molecules, while F^- has strong hydration ability and interacts strongly with water. The coexistence of these two anions may therefore regulate the interfacial environment. Such an interfacial structure could reduce the approach and accumulation of Cl^- , thereby protecting NiFe-LDH from chloride-induced corrosion and metal dissolution during OER. Overall, the $\text{F}^- + \text{B(OH)}_4^-$ electrolyte provides a simple strategy to improve catalyst stability by regulating the local electrolyte environment rather than modifying the catalyst itself.

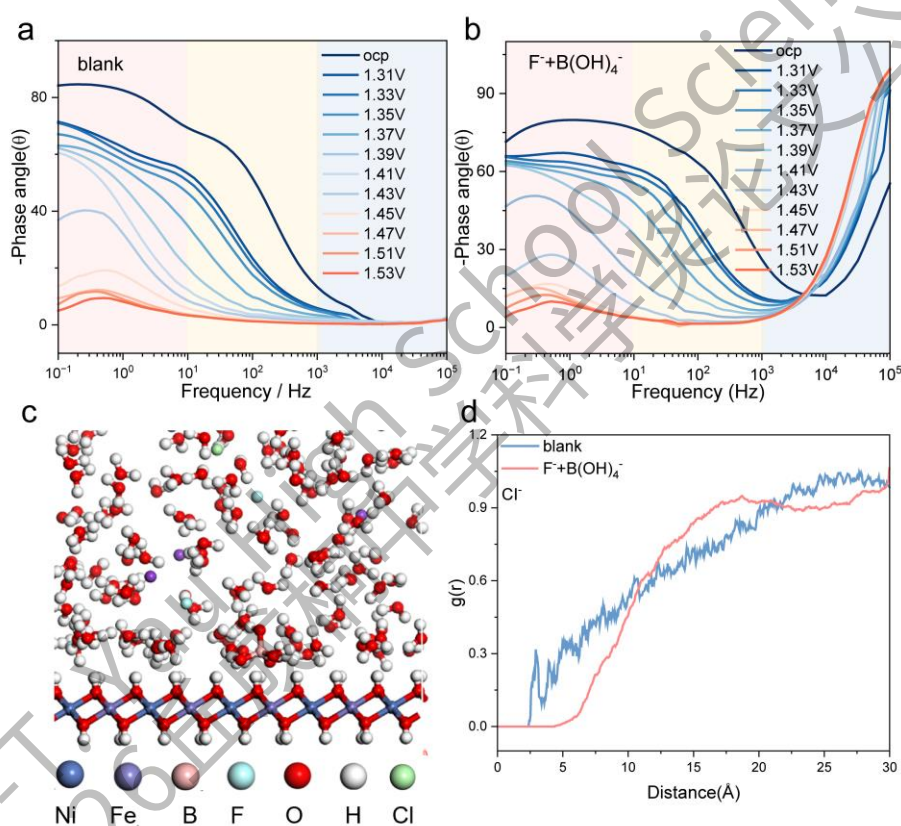


Figure 4. In situ EIS of NiFe-LDH in the ASSE (a) in blank and (b) $\text{F}^- + \text{B(OH)}_4^-$ electrolytes. (c) Representative molecular-dynamics snapshot of the NiFe-LDH/electrolyte. (d) The radial distribution of Cl^- in different systems.

4. Conclusions

In this work, a simple dual-anion electrolyte strategy was developed to improve the durability of NiFe-LDH for alkaline saline-water oxidation. Systematic optimization identified 1.5 M $\text{F}^- + 0.4 \text{ M } \text{B(OH)}_4^-$ as the optimal electrolyte composition,

decreasing the overpotential at 10 mA cm^{-2} from approximately 234 mV in the blank electrolyte to 225 mV and enabling stable operation at 1 A cm^{-2} for over 1500 h, compared with failure of the blank system after approximately 600 h. XPS and operando Raman spectroscopy supported the presence and interaction of F^- and borate species at the catalyst/electrolyte interface, while ICP-OES measurements showed substantially reduced Ni and Fe dissolution, confirming enhanced resistance to catalyst degradation. Operando Bode analysis further revealed faster OER-related interfacial processes together with a pronounced high-frequency capacitive response in the dual-anion electrolyte. Combined with MD simulations showing that the closest distribution of Cl^- was shifted away from the NiFe-LDH surface, these results suggest that F^- and B(OH)_4^- cooperatively regulate the local interfacial environment. The hydroxyl-rich B(OH)_4^- and strongly hydrated F^- may regulate the interfacial environment and restrict Cl^- accumulation near the catalyst, thereby suppressing corrosion and metal dissolution. This work demonstrates that rational electrolyte engineering provides a simple and effective approach to simultaneously enhance OER activity and long-term stability without requiring complicated modification of the catalyst itself, offering a promising strategy for durable alkaline saline-water electrolysis.

5. References

- 1 Sha Q, Wang S, Yan L, et al. 10,000-h-stable intermittent alkaline seawater electrolysis. *Nature*, **2025**, 639: 360
- 2 Zhou D, Li P, Lin X, et al. Layered double hydroxide-based electrocatalysts for the oxygen evolution reaction: Identification and tailoring of active sites, and superaerophobic nanoarray electrode assembly. *Chem Soc Rev*, **2021**, 50: 8790
- 3 Liu D, Cai Y, Wang X, et al. Innovations in electrocatalysts, hybrid anodic oxidation, and electrolyzers for enhanced direct seawater electrolysis. *Energy Environ Sci*, **2024**, 17: 6897
- 4 Huang J, Hu B, Meng J, et al. Highly efficient sustainable strategies toward carbon-neutral energy production. *Energy Environ Sci*, **2024**, 17: 1007
- 5 Tong W, Forster M, Dionigi F, et al. Electrolysis of low-grade and saline surface water. *Nat Energy*, **2020**, 5: 367
- 6 Zhao C, Wang S. Harnessing dynamic reconstruction for intermittent seawater electrolysis. *Joule*, **2025**, 9: 101969
- 7 Zeng P, Yuan C, Su B, et al. Unraveling the catalytic redox mechanism of lithium–sulfur batteries through advanced in-situ/operando characterizations. *Sci China Chem*, **2025**, 68: 1810
- 8 Dionigi F, Reier T, Pawolek Z, et al. Design criteria, operating conditions, and nickel–iron hydroxide catalyst materials for selective seawater electrolysis. *Chem Sus Chem*, **2016**, 9: 962-
- 9 Wu Z-J, Li J-H, Ying J, et al. Chloride ions resistance strategies in seawater electrolysis. *Small*, **2025**, 21: 2504302
- 10 Trotochaud L, Young SL, Ranney JK, et al. Nickel–iron oxyhydroxide oxygen-evolution electrocatalysts: The role of intentional and incidental iron incorporation. *J Am Chem Soc*, **2014**, 136: 6744
- 11 Dresp Sr, Dionigi F, Klingenhof M, et al. Direct electrolytic splitting of seawater: Opportunities and challenges. *ACS Energy Lett*, **2019**, 4: 933
- 12 Kuang Y, Kenney MJ, Meng Y, et al. Solar-driven, highly sustained splitting of seawater into hydrogen and oxygen fuels. *Proc Natl Acad Sci*, **2019**, 116: 6624
- 13 Cheng J, Liu W, Chen S, et al. Fluoride-engineered electrolyte for highly stable and efficient alkaline seawater electrolysis at 2 a cm⁻². *Angew Chem Int Ed*, **2025**, 64: e18106
- 14 Yang L, Xing Z, Chen Y, et al. Anion shielding in nb-wo₃/ws₂ heterostructures: A strategy for efficient and corrosion-resistant seawater electrolysis. *Small*, **2025**, 21: e09761
- 15 Liu T, Chen Y, Hao Y, et al. Hierarchical anions at the electrode-electrolyte interface for synergized neutral water oxidation. *Chem*, **2022**, 8: 2700

- 16 Liu Y, Guo J, Liu X, et al. Corrosion-driven ni₃s₄ gradient in nife-ldh enables durable industrial-scale water electrolysis. *Angew Chem Int Ed*, **2025**, 64: e202516894
- 17 Liu W, Yu J, Sendeku MG, et al. Ferricyanide armed anodes enable stable water oxidation in saturated saline water at 2 a/cm². *Angew Chem Int Ed*, **2023**, 62: e202309882
- 18 Liu W, Yu J, Li T, et al. Self-protecting cofeal-layered double hydroxides enable stable and efficient brine oxidation at 2 a cm⁻². *Nat Commun*, **2024**, 15: 4712
- 19 Yu M, Li J, Liu F, et al. Anionic formulation of electrolyte additive towards stable electrocatalytic oxygen evolution in seawater splitting. *J Energy Chem*, **2022**, 72: 361
- 20 He X, Yao Y, Zhang L, et al. Hexafluorophosphate additive enables durable seawater oxidation at ampere-level current density. *Nat Commun*, **2025**, 16: 4998
- 21 Lu Z, Xu W, Zhu W, et al. Three-dimensional nife layered double hydroxide film for high-efficiency oxygen evolution reaction. *Chem Commun*, **2014**, 50: 6479
- 22 Ou Y, Twight L, Samanta B, et al. Cooperative Fe sites on transition metal (oxy)hydroxides drive high oxygen evolution activity in base. *Nat Commun*, **2023**, 14:7688
- 23 Zhang B, Liu S, Zhang S, et al. High corrosion resistance of nife-layered double hydroxide catalyst for stable seawater electrolysis promoted by phosphate intercalation. *Small*, **2022**, 18: 2203852
- 24 Jeong S, Kim U, Lee S, et al. Superaerophobic/superhydrophilic multidimensional electrode system for high-current-density water electrolysis. *ACS Nano*, **2024**, 18: 7558
- 25 Li P, Duan X, Kuang Y, et al. Tuning electronic structure of nife layered double hydroxides with vanadium doping toward high efficient electrocatalytic water oxidation. *Adv Energy Mater*, **2018**, 8: 1703341
- 26 Shi Y, Song L, Liu Y, et al. Dual cocatalytic sites synergize nife layered double hydroxide to boost oxygen evolution reaction in anion exchange membrane water electrolyzer. *Adv Energy Mater*, **2024**, 14: 2402046
- 27 Li Y, Wang J-H, Liu T-Y, et al. Enhancing lithium storage rate and durability in sphalerite gep by engineering configurational entropy. *Energy Environ Sci*, **2024**, 17: 6533
- 28 Zhao K, Tao Y, Fu L, et al. Bifunctional near-neutral electrolyte enhances oxygen evolution reaction. *Angew Chem Int Ed*, **2023**, 62: e202308335
- 29 Guo L, Chi J, Cui T, et al. Phosphorus defect mediated electron redistribution to boost anion exchange membrane-based alkaline seawater electrolysis. *Adv Energy Mater*, **2024**, 14: 2400975

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