Supporting Information

Oxyanions as dynamic regulators of the oxygen evolution reaction

Yao Wang,[a‡] Haoyu Li,[a‡] Junyuan Duan, [a*] and Wenbin Wang[b*]

[a]State Key Laboratory of Green and Efficient Development of Phosphorous Resource, Hubei Key Laboratory of Plasma Chemistry and New Materials, School of Chemistry and Environmental Engineering, School of Materials Science and Engineering, Wuhan Institute of Technology, Wuhan 430205, China.

[b]Key Laboratory of Luminescence Analysis and Molecular Sensing, Ministry of Education, and School of Chemistry and Chemical Engineering, Southwest University, Chongqing 400715,China

E-mail: junyduan@wit.edu.cn, wangwenbin@swu.edu.cn

‡These authors contributed equally to this work.

Table S1. Oxyanions acting as dominant Type I electronic-structure regulators

Oxyanions	Classification	Key mechanism	Ref.
TeO_3^{2-} /TeO_4^{2-}	$I_d + III_w$	Te and S in CoTe@CoS are oxidized into TeO_3^{2-}/TeO_4^{2-} that bind to CoOOH, tuning the Co d-band, enhancing adsorption, improving electron transport, and optimizing OH- distribution.	S1
SO_3^{2-}/SO_4^{2-}	$I_d + III_w$	$FeNiS_2$ reconstructs, forming SO_3^{2-}/SO_4^{2-} bound to NiFeOOH, electrolyte sulfate limits loss, stabilizes Fe sites, enhances OH/OOH adsorption, shifts the d-band, and lowers the reaction energy barrier.	S2
SO_4^{2-}	$I_d + III_w$	SO_4^{2-} formed in-situ on NiFe alloy by pyrolysis shifts the d-band center, weakens metal-oxygen interactions, lowers energy barriers, enhances charge transfer, improves hydrophilicity, and stabilizes adsorption.	S3
SO_4^{2-}	$I_d + III_s$	SO_4^{2-} intercalates into HELDH, forming hydrogen-bonded superlattice that optimizes electronic structure, promotes active phase formation, enhances mass transport, and maintains long-term catalytic stability through strong coordination and a robust porous framework.	S4
SO_4^{2-}	$I_d + III_s$	In S-$NiMoO_4$, S converts to SO_4^{2-}during OER, shifting the d-band center toward the Fermi level, enhancing OH adsorption, generating Ni^{4+} species, accelerating kinetics, and stabilizing the surface.	S5
MoO_4^{2-}	$I_d + III_s$	MoO_4^{2-} forms in situ during OER and adsorbs on γ-NiFeOOH via Ni-O-Mo bond, enhancing charge transfer, tuning Ni electronic structure, lowering barriers, repelling Cl^-, and improving corrosion resistance.	S6
NO_3^-	$I_d + III_w$	NO_3^- selectively re-adsorbed after in-situ dissolution from NiFeNH, enhances electron transfer, tunes Fe d-band, lowers OER energy barrier, and promotes OH transport and bubble release, boosting stability.	S7
NO_3^-	$I_d + III_w$	NO_3^- is embedded to form FeOOH/$Ni_3(NO_3)_2(OH)_4$ heterointerface, enhancing Fe binding, suppressing over-oxidation/dissolution, and improving charge distribution, mass transport, and OER stability.	S8
CrO_4^{2-}	$I_d + III_s$	CrO_4^{2-} enhances Ni-3d electron density, promotes NiOOH formation, lowers OER barriers, shifts mechanism to LOM, and creates environment that favors OH^-, repels Cl^-, and improves corrosion resistance.	S9
PO_4^{3-}	$I_d + III_w$	PO_4^{3-} binds CoFe oxide, lengthening Co-O bonds, upshifting Co 3d and O 2p centers, enhancing OH adsorption, enabling LOM, and improving reconstruction, oxygen cycling, and stability	S10
PO_4^{3-}	$I_d + III_s$	As electrolyte additive, PO_4^{3-} bind Ni/Fe sites, modulating electronics, suppressing dissolution and cathode poisoning, maintaining superoleophobicity, and preserving efficient interfacial mass transport.	S11
BO_3^{3-}/CO_3^{2-}	$I_d + III_s$	Their role is the same as the PO_4^{3-} in ref.S10.	S11
HCO_3^- /CO_3^{2-}	$I_d + III_s$	CO_3^{2-} removal creates ligand vacancies partly filled by hydroxide, stabilizing $Ni(OH)_x$, tuning d orbitals, reducing deprotonation energy, enabling reversible Ni redox, repelling OH, and promoting NOR.	S12
MoO_4^{2-} /SO_4^{2-}	$I_d + III_s$	MoO_4^{2-} and SO_4^{2-} formed in situ during sacrificial heterojunction reconstruction, bind to NiOOH, tunes Ni electronic structure and Ni-O bonding, optimizes OER energetics, and suppressing metal dissolution.	S13

Table S1. (continued)

Oxyanions	Classification	Key mechanism	Ref.
SO_4^{2-}	$I_d + III_s$	SO_4^{2-} generated leaching and re-adsorption from NiFeS enhances M-O covalency, strengthens Fe-O/Ni-O bond, suppresses Fe dissolution, and forms a permeable layer that improves mass transfer and hydrophilicity.	S14
MoO_4^{2-}	$I_d + III_s$	MoO_4^{2-} formed during pre-leaching, with minor sulfate from S oxidation, anchors on NiFeO(S)OH via Ni-O-Mo, enhancing charge transfer, strengthening M-S bonds, and improving interfacial kinetics and stability.	S15
SO_4^{2-} /SeO_4^{2-}	$I_d + III_s$	SO_4^{2-}/SeO_4^{2-} formed via in situ oxidation of NiFeS(Se), adsorb on NiFeOOH, tune Fe electronic structure, enhances coupling, accelerate PCET, and reorganize interfacial hydrogen bond networks.	S16
PO_4^{3-}	$I_d + III_s$	PO_4^{3-} grown and intercalated into NiFe-LDH, modulating metal valence, electronic structure, and covalency to promote γ-NiOOH formation while enhancing hydrophilicity, mass transport, and chloride repulsion.	S17
PO_4^{3-}	$I_d + III_s$	PO_4^{3-} enters NiFe LDH interlayers and adsorbs on surfaces via hydrothermal process, tuning electronic structure, expanding spacing, enhancing mass transport, and increasing active sites, thereby improving catalytic efficiency.	S18
SO_4^{2-}	I	SO_4^{2-} anchored sulfate formed in situ from WS_2 oxidation binds strongly to RuO_2 via Ru-O-S, alters electronic distribution, weakens Ru-O covalency, and optimizes intermediate adsorption	S19
SnO_3^{2-}	$I_d + III_s$	In situ reconstruction generates SnO_3^{2-} from Sn oxidation, anchoring within NiOOH, enhance adsorption and dehydrogenation, suppress OER, expand layers, and reduce OH^- competition.	S20
CO_3^{2-}	$I_d + III_s$	CO_3^{2-} formed in situ uniformly adsorbs on NiOOH, electronically couples with Ni, tunes 3d levels, enhances urea activation, stabilizes intermediates, lowers barriers, suppresses OER, and improves selectivity.	S21
PO_4^{3-}/SO_4^{2-}/CO_3^{2-} /BO_3^{3-}	$I_d + III_s$	PO_4^{3-}/SO_4^{2-}/CO_3^{2-}/BO_3^{3-} bind Ni-based catalysts by tuning electronic structure, stabilizing intermediates, enhancing biomass oxidation, suppressing OER, and improving mass transfer.	S22
PO_4^{3-}	$I_d + III_s$	PO_4^{3-} binds to NiFeOOH via interlayer intercalation and surface coordination, tuning the d-band center, enhancing adsorption, ion transport, and lowering the oxygen evolution barrier.	S23
SO_4^{2-}	$I_d + III_s$	SO_4^{2-} formed by in situ electrochemical activation binds transition metal oxyhydroxides, tuning the d-band center, facilitating intermediates, accelerating PCET, and preventing deactivation by repelling harmful ions.	S24
		The electrolyte supplies PO_4^{3-} that chemisorb on FeOOH, tune	

		its electronic structure, optimize adsorption, accelerate proton transfer, stabilize pH, enhance corrosion resistance, and promote a more active mixed phase.	
CO_3^{2-}	$I_d + III_s$	CO_3^{2-} introduced in situ or through the electrolyte binds Ni(OH)2, tuning electronic structure, optimizing intermediate adsorption, enhancing mass transport, expanding active sites, and improving stability at high currents.	S26
$PO_4^{3-}/SO_4^{2-}/CO_3^{2-}$	$I_d + III_s$	$PO_4^{3-}/SO_4^{2-}/CO_3^{2-}$ bind to the NiFeCo catalyst, tuning electronic structure and defects, stabilizing the interface and pH, and enabling controlled reconstruction with sustained catalytic activity and durability.	S27

Table S1. (continued)

Oxyanions	Classification	Key mechanism	Ref.
MoO_4^{2-}	$I_d + III_s$	In situ reconstruction of $NiMoO_4$/NiFe LDH releases and anchors MoO_4^{2-}, tuning electronic structure and OER energetics while expanding spacing, improving hydroxide transport, stabilizing pH, and preventing degradation.	S28
PO_4^{3-} + SO_4^{2-}	$I_d + III_s$	PO_4^{3-} and SO_4^{2-} from in situ oxidation and self-reconstruction of Fe-doped Ni thiophosphate, including PO4 and SO4, modulate structure, enhance adsorption, stabilize surfaces, and promote PCET and mass transport.	S29
SO_4^{2-}	$I_d + III_s$	SO_4^{2-} anchored on N-doped Co_3O_4 nanosheets modulate electronic structure, optimize intermediate adsorption, enhance hydrophilicity, speed mass transfer, and prevent active site deactivation via electrostatic repulsion.	S30
CrO_4^{2-}	$I_d + III_s$	CrO_4^{2-} intercalates into NiFe LDH, repels chloride ions, enhances hydroxide adsorption, improving OER selectivity and stability.	S31
$P_3O_{10}^{5-}$	$I_d + III_s$	$P_3O_{10}^{5-}$ modifies $Ni(OH)_2$ via CV, raising Ni valence, improving OER activity and selectivity, suppressing ClOR, and enhancing stability through electrostatic repulsion, pH regulation, and surface passivation.	S32
NO_3^- /PO_4^{3-} /SO_4^{2-} /SeO_4^{2-}	$I_d + III_w$	NO_3^-, PO_4^{3-}, SO_4^{2-}, or SeO_4^{2-} are introduced onto NiFeCoOOH via CV, tuning metal 3d and oxygen 2p orbitals. NO_3^- and PO_4^{3-} improve stability and activity, while SO_4^{2-}, and SeO_4^{2-} reduce performance.	S33
SO_4^{2-}	I	Sulfate ions formed in situ anchor on RuO_2 via barium, creating a Ru-O-S-O-Ba bridge that matches the surface and converts bridging oxygens to three-coordinated sites.	S34
MoO_4^{2-}	$I_d + III_s$	Electrodeposition-driven MoO_4^{2-} intercalation in NiFe-LDH tunes Ni/Fe d band centers, optimizes intermediate adsorption, shifts rate-determining steps, and EDL enrichment accelerates OH desorption and ion migration.	S35
SO_4^{2-}	I	SO_4^{2-} formed in situ from oxidized NiFeS and anchored on $NiFe_2O_4$ modulate adjacent octahedral Ni, converting Ni^{2+} to OER optimal Ni^{3+}.	S36
SO_4^{2-}	I	S in MoS_2 oxidizes in air to SO_4^{2-}, which binds RuO_2, tunes adsorption, lowers energy barriers, enhances acidic OER activity, and improves stability by suppressing Ru dissolution and structural degradation	S37

I, II, and III denote Type I (electronic-structure regulators), Type II (charge-buffering/electron-relay species), and Type III (microenvironment regulators), respectively. Subscripts d, w, and s indicate dominant, weak, and synergistic roles.

Table S2. Oxyanions acting as dominant Type II charge-buffering and electron-relay species[1]

Oxyanions	Classification	Key mechanism	Ref.
FeO_4^{2-}	$II_d + I_w$	Surface Fe in NiFe hydroxides dissolves under OER potentials to form FeO_4^{2-}, cycling via reabsorption, coupling with oxygen intermediates, mediating electron transfer, and enabling O-O formation and self-healing.	S38
FeO_4^{2-}	$II_d + I_w$	Electrolyte-derived FeO_4^{2-} promotes multi-electron transfer, enables dissolution-redeposition to sustain active sites, enhance charge transport, and tune Ni/Co electronic structure for improved oxygen evolution kinetics	S39
$(W_2O_7)^{2-}$	II	CeO_2-modified NiFe LDH intercalated with $(W_2O_7)^{2-}$ uses reversible W^{5+}/W^{6+} redox buffering; M-O-W bridges and proton coupling enhance transport, reduce barriers, and improve seawater OER performance.	S40
$[PW_{12}O_{40}]^{3-}$	$II_d + I_{w+} III_w$	$[PW_{12}O_{40}]^{3-}$ on CoFe LDH as an electron relay, lowering charge resistance, stabilizing Fe against dissolution, and tuning Co sites to favor OH over Cl, enabling long-term efficient seawater OER.	S41
$[PMo_{12}O_{40}]^{3-}$	$II_d + I_{w+} III_w$	The role is the same as $[PW_{12}O_{40}]^{3-}$	S41
$[PSi_{12}O_{40}]^{4-}$	$II_d + I_{w+} III_w$	The role is the same as $[PW_{12}O_{40}]^{3-}$	S41
MoO_4^{2-}	II	acts as a redox-active species, reversibly cycling between Mo^{6+} and Mo^{5+} under OER anodic potentials, enabling dynamic redistribution of interfacial charge.	S42

I, II, and III denote Type I (electronic-structure regulators), Type II (charge-buffering/electron-relay species), and Type III (microenvironment regulators), respectively. Subscripts d, w, and s indicate dominant, weak, and synergistic roles.

Table S3. Oxyanions acting as dominant Type III microenvironment regulators

Oxyanions	Classification	Key mechanism	Ref.
SeO_3^{2-}/SeO_4^{2-}	$III_d + I_w$	SeO_3^{2-} and SeO_4^{2-} formed from Ni_xSe under anodic OER conditions, adsorb on NiOOH, weakly tuning active sites, optimizing intermediate adsorption, and enhancing activity via subtle interfacial electrostatic effects.	S43
SO_4^{2-}	$III_d + I_w$	Under OER conditions, SO_4^{2-} adsorbs on NiCoOOH, forming a hydrogen-bond network that enhances water structure, accelerates OH^- transport, optimizes electronic states, lowers energy barriers, and promotes high-valence active phase formation.	S44
SO_4^{2-} /CO_3^{2-} /NO_3^-	III	Externally added SO_4^{2-}, CO_3^{2-}, and NO_3^- adsorb at the inner Helmholtz plane, displacing OH and lowering its interfacial concentration, disrupting equilibrium and promoting OH release, accelerating surface reconstruction.	S45
NO_3^-	$III_d + I_s$	Surface-adsorbed NO_3^- on NiFe LDH builds negative charge, repelling chloride and lowering capacitance, while restructuring interfacial water to hinder ion diffusion, enhance hydroxide transport, and stabilize active sites, improving oxygen evolution performance.	S46
NO_3^-/CO_3^{2-}	III	NO_3^- and CO_3^{2-} in NiFe-LDH interlayers leach out and are replaced by hydroxide, decreasing layer thickness, increasing spacing and distortion, and promoting Fe^{2+}-rich substitution.	S47
MoO_4^{2-}/SO_4^{2-}	$III_d + I_s$	During OER on the (Ni,Fe)S_2/MoS_2 heterostructure, MoO_4^{2-} and SO_4^{2-} guide precatalyst reconstruction, modulating active sites and promoting asynchronous Ni and Fe oxidation.	S48
$-SO_3^-$	III	$-SO_3^-$ groups are covalently attached to the Ir/IrOx surface, creating a hydrogen-bond network that enhances proton transport, promotes PCET, facilitates OOH formation, and improves stability in acidic OER conditions.	S49
SO_4^{2-}	III	Externally added components and barium-fixed sulfate use electrostatic repulsion, steric hindrance, and competitive adsorption to form a protective layer that suppresses chloride corrosion and enables dynamic self-healing.	S50
CO_3^{2-}	III	Nickel oxalate converts in situ to CO_3^{2-} on NiOOH, forming a weakly bound interface that depletes hydroxide, suppresses OER over a wide range.	S51
CO_3^{2-}	$III_d + I_s$	CO_3^{2-} formed during NiFe oxalate transformation is charged, repels chloride, suppresses side reactions, enhances NiFeOOH activity, and stabilizes a protective layer for sustained seawater oxidation.	S52
MoO_4^{2-}	III	MoO_4^{2-} formed in situ from RuMoNi creates a stable negatively charged layer via reversible NiMoO4, repelling chloride, limiting corrosion and side reactions, and sustaining high-current oxygen evolution.	S53

$PO_4^{3-}/SO_4^{2-}/ClO_4^-/NO_3^-$	III	Oxyanions tune Helmholtz layer thickness and interfacial fields, affecting Ir-site solvation, adsorption, proton transfer, and stability, with adsorption strength ranking phosphate > sulfate >> nitrate ≈ perchlorate.	S54
$B(OH)_4^-/BO_3^{3-}$	III	$B(OH)_4^-/BO_3^{3-}$ briefly adsorbs on NiFe hydroxide, stabilizing charge during potential fluctuations, buffering interfacial pH, regulating the double layer, and limiting reconstruction, dissolution, and activity loss.	S55

Table S3 (continued)

Oxyanions	**Classification** Type (I, II, III)	**Key mechanism**	**Ref.**
PO_4^{3-}	III	Post phosphorylation introduces phosphate species that promote proton transfer, accelerate PCET, improve hydration, stabilize intermediates, enhance kinetics, and reinforce oxide stability for efficient, durable, noble-metal-free OER catalysis.	S56
BO_3^{3-} /$B(OH)_4^-$	III	Exogenous borate in the electrolyte buffers interfacial protons, stabilizes pH, accelerates proton coupled electron transfer, optimizes hydration, improves mass transport, and enhances stability and corrosion resistance.	S57
WO_4^{2-}	III	In situ formed WO_4^{2-} serves as a surface Bronsted base, increasing local hydroxide levels, facilitating water splitting, and improving OH adsorption and activation on NiCoOOH sites.	S58
RuO_5^{2-}	III	The honeycomb ATO nanocavities restrict outward diffusion of soluble RuO_5^{2-}, increasing its surface concentration and shifting equilibrium to suppress RuO_2 over-oxidation and degradation.	S59
PO_4^{3-} +CO_3^{2-}	III	During OER, the phytic-acid shell oxidizes into phosphate and carbonate, forming an oxyanion layer on NiFeOOH that blocks halides, suppresses dissolution, enhances mass transport, and tunes structure.	S60
SiO_3^{2-}	III	SiO_3^{2-} weakly adsorb on $Ni(OH)_2$, restructuring hydrogen bond networks, boosting water dissociation, repelling chloride, enhancing hydrophilicity, promoting Ni oxidation, and improving seawater OER activity and stability.	S61

I, II, and III denote Type I (electronic-structure regulators), Type II (charge-buffering/electron-relay species), and Type III (microenvironment regulators), respectively. Subscripts d, w, and s indicate dominant, weak, and synergistic roles.

References

S1 W. W. Bao, J. Y. Liu, T. T. Ai, J. Han, J. A. Hou, W. H. Li, X. L. Wei, X. Y. Zou, Z. F. Deng and J. J. Zhang, Adv. Funct. Mater., 2024, 34, 2408364.

S2 Q. M. Chen, Q. C. Zhang, B. Chen, J. H. Zhang, W. C. Peng, Y. Li and X. B. Fan, Adv. Funct. Mater., 2024, 34, 2406233.

S3 Y. C. Jin, X. J. Qu, Z. H. Zhou, R. N. Liu, M. X. Zhang, L. Song, W. Q. Ma and M. D. Zhang, Small, 2025, 21, 2408171.

S4 Y. Liu, X. R. Jiao, X. M. Jiang, C. C. Xing, X. Q. Qi, X. Wang and A. Cabot, ACS Nano, 2026, 20, 6732-6741.

S5 A. Satheesan, V. Parey, A. Karmakar, R. Madhu, S. Nagappan, S. S. Roy, P. Mazumder, R. Thangamuthu, S. Chakraborty and S. Kundu, Small, 2025, 21, e08560.

S6 L. Shao, X. Han, L. Shi, T. Wang, Y. Zhang, Z. Jiang, Z. Yin, X. Zheng, J. Li, X. Han and Y. Deng, Adv. Energy Mater., 2024, 14, 2303261.

S7 W. B. Wang, Q. L. Wen, D. J. Huang, Y. Lin, N. D. Zhao, L. Tang, M. Li, Y. W. Liu and R. X. He, Angew. Chem. Int. Ed., 2025, 64, e202415132.

S8 H. X. Liao, G. H. Ni, P. F. Tan, K. Liu, X. Z. Liu, H. L. Liu, K. J. Chen, X. S. Zheng, M. Liu and J. Pan, Adv. Mater., 2023, 35, 2300347.

S9 C. X. Liu, Z. F. Teng, X. Liu, R. Zhang, J. Q. Chi, J. W. Zhu, J. F. Qin, X. B. Liu, Z. X. Wu and L. Wang, Chem. Sci., 2025, 16, 16321-16330.

S10 X. He, M. Liu, F. Liu, X. Liu, H. Liao, P. Tan and J. Pan, Adv. Funct. Mater., 2025, 35, e05936.

S11 W. Liu, X. Q. Ding, J. J. Cheng, J. L. Jing, T. S. Li, X. Huang, P. P. Xie, X. C. Lin, H. L. Ding, Y. Kuang, D. J. Zhou and X. M. Sun, Angew. Chem. Int. Ed., 2024, 63, e202406082.

S12 X. K. Liu, C. X. Shi, G. Zhang, R. J. Gao, L. Pan, X. W. Zhang, Z. F. Huang, J. L. Gong and J. J. Zou, Nat. Commun., 2025, 16, 11224.

S13 N. Zhao, Q. Wen, Z. Lui, Y. Jiang, M. Li, W. Wang, Y. Liu and R. He, Adv. Energy Mater., 2026, 16, e04712.

S14 Y. Lin, J. K. Fang, W. B. Wang, Q. L. Wen, D. J. Huang, D. F. Ding, Z. Li, Y. W. Liu, Y. Shen and T. Y. Zhai, Adv. Energy Mater., 2023, 13, 2300604.

S15 Y. Lin, D. J. Huang, Q. L. Wen, R. O. Yang, B. W. Chen, Y. Shen, Y. W. Liu, J. K. Fang, H. Q. Li and T. Y. Zhai, Proc. Natl. Acad. Sci. U.S.A., 2024, 121, e2407350121.

S16 K. Y. Wang, S. Y. Li, J. K. Li, C. Liang, J. Y. Li, L. F. Lei, M. H. Zhu, L. Z. Zhuang, J. Chen, Z. Xu and X. D. Yao, Angew. Chem. Int. Ed., 2025, 64, e202511112.

S17 L. Ye, Z. P. Chen, X. Y. Xu, F. Ma, K. C. Fan, L. B. Zong, L. Wang, G. J. Chen, X. W. Li and T. R. Zhan, Inorg. Chem., 2024, 63, 20859-20869.

S18 S. Q. Ding, B. Zheng, X. F. Wang, Y. Zhou, Z. R. Pan, Y. Chen, G. X. Liu and L. M. Lang, Langmuir, 2024, 40, 10384-10392.

S19 L. Q. Li, B. H. Zhou, X. Z. Liu, F. Liu, M. H. Liu, Y. Yu, H. H. Zhai, P. F. Tan and J. Pan, Chem. Eng. J., 2026, 528, 172760.

S20 W. J. Jiang, J. L. Zhang, J. Wu, Z. X. Zhai, T. Q. Yu, L. Luo and S. B. Yin, Adv. Energy Mater., 2026, 16, e03978.

S21 L. Q. Hou, C. Y. Sun, Z. Y. Zhang, H. Jang, Z. J. Li, M. G. Kim, J. Cho, S. G. Liu and X. Liu, Adv. Funct. Mater., 2026, 36, e19865.

S22 P. H. Xu, Z. Y. Bao, Y. J. Zhao, L. X. Zheng, Z. Q. Lv, X. W. Shi, H. E. Wang, X. S. Fang and H. J. Zheng, Adv. Energy Mater., 2024, 14, 2303557.

S23 H. X. Xu, K. Li, N. Liu, W. Xia, W. H. Liu, D. Cao, L. P. Zhang and D. J. Cheng, Catal. Sci. Technol., 2023, 13, 6780-6791.

S24 L.-W. Shen, Y. Wang, L. Shen, J.-B. Chen, Y. Liu, M.-X. Hu, W.-Y. Zhao, K.-Y. Xiong, S.-M. Wu, Y. Lu, J. Ying, M. M. Titirici, C. Janiak, G. Tian and X.-Y. Yang, Energy Environ. Sci., 2024, 17, 3888-3897.

S25 X. Q. Du, J. J. Zhang, M. Y. Zhang, H. L. Wei, X. Lin, W. Guo, P. F. Zhang and Z. H. Luo, Green Chem., 2025, 27, 7380-7388.
S26 H. Komiya, K. Obata, T. Honma and K. Takanabe, J. Mater. Chem. A, 2024, 12, 3513-3522.
S27 L. Jiang, X. Chen, L. Jiang, X. Luo, R. Li, Q. Zhou, X. Mu, L. Chen, J. Yu and S. Mu, Nano Lett., 2025, 25, 13875-13884.
S28 S. Zhang, M. Cen, Q. Wang, X. Luo, W. Peng, Y. Li, F. Zhang and X. Fan, Chem. Commun., 2023, 59, 3427-3430.
S29 B. Kirubasankar, Y. S. Won, S. H. Choi, J. W. Kim, L. A. Adofo, S. M. Kim and K. K. Kim, Chem. Commun., 2023, 59, 9247-9250.
S30 H. Yang, Y. Y. Wan, S. K. Yang, X. C. Zhou, S. Gao, D. W. Rao and W. D. Shi, Small, 2025, 21, 2505719.
S31 Z. W. Cai, J. Liang, Z. X. Li, T. Y. Yan, C. X. Yang, S. J. Sun, M. Yue, X. W. Liu, T. Xie, Y. Wang, T. S. Li, Y. S. Luo, D. D. Zheng, Q. Liu, J. X. Zhao, X. P. Sun and B. Tang, Nat. Commun., 2024, 15, 6624.
S32 X. L. Wang, H. S. Hu, J. N. Song, J. Q. Ma, H. X. Du, J. J. Wang, M. Wang, W. Chen, Y. Zhou, J. C. Wang, M. H. Yang and L. X. Zhang, Adv. Energy Mater., 2025, 15, 2402883.
S33 X. Wang, R. Ma, S. Li, M. Xu, L. Liu, Y. Feng, T. Thomas, M. Yang and J. Wang, Adv. Energy Mater., 2023, 13, 2300765.
S34 Y. R. Xue, J. W. Zhao, L. Huang, Y. R. Lu, A. Malek, G. Gao, Z. B. Zhuang, D. S. Wang, C. T. Yavuz and X. Lu, Nat. Commun., 2023, 14, 8093.
S35 Q. Zhang, W. Xiao, J. X. Shi, J. L. Lei, Q. Xiao, H. Q. Luo and N. B. Li, ACS Catal., 2024, 14, 18003-18017.
S36 T. Zhang, Y. P. Liu, L. Tong, J. Yu, S. W. Lin, Y. Li and H. J. Fan, ACS Nano, 2023, 17, 6770-6780.
S37 Y. Duan, L. L. Wang, W. X. Zheng, X. L. Zhang, X. R. Wang, G. J. Feng, Z. Y. Yu and T. B. Lu, Angew. Chem. Int. Ed., 2024, 63, e202413653.
S38 C. G. Kuai, L. P. Liu, A. Y. Hu, Y. Zhang, Y. X. Zhang, D. W. Xia, D. Nordlund, D. Sokaras, D. Decarolis, D. Gianolio, H. L. Xin, L. X. Li and F. Lin, Nat. Catal., 2025, 8, 523-535.
S39 H. Y. Li, Y. W. Zhang, Y. B. Chen, Y. Li, Z. J. Li, B. Yang, Q. H. Zhang, J. G. Lu, L. C. Lei, Z. C. Xu and Y. Hou, Angew. Chem. Int. Ed., 2025, 64, e202423071.
S40 M. Li, H.-J. Niu, Y. Li, J. Liu, X. Yang, Y. Lv, K. Chen and W. Zhou, Appl. Catal. B, 2023, 330, 122612.
S41 X. He, Y. C. Yao, M. Zhang, Y. L. Zhou, L. M. Zhang, Y. C. Ren, K. Dong, H. Tang, J. Nan, X. L. Zhou, H. Luo, B. W. Ying, Q. Yu, F. M. Luo, B. Tang and X. P. Sun, Nat. Commun., 2025, 16, 5541.
S42 H.-F. Wang, C. Tang, B.-Q. Li and Q. Zhang, Inorg. Chem. Front., 2018, 5, 521-534.
S43 M. L. Tu, Z. X. Zhu, Y. X. He, S. Mathi, J. Q. Deng, M. Naushad, Y. C. Huang, Y. W. Hu and M. S. Balogun, Small, 2025, 21, 2500687.
S44 Y. Lin, B. W. Chen, D. J. Huang, Z. H. Yang, A. Lu, Z. Y. Shi, Y. W. Liu, J. K. Fang, H. Q. Li and T. Y. Zhai, Angew. Chem. Int. Ed., 2025, 64, e202502151.
S45 Y. Tang, C. Wu, Q. Zhang, H. Y. Zhong, A. Q. Zou, J. H. Li, Y. F. Ma, H. An, Z. G. Yu, S. B. Xi, J. M. Xue, X. P. Wang and J. G. Wu, Angew. Chem. Int. Ed., 2023, 62, e202309107.
S46 C. Y. Sun, Z. Y. Zhang, H. Jang, Z. J. Li, M. G. Kim, J. Cho, S. G. Liu, X. Liu and L. Q. Hou, Sci. China Chem., 2026, 69, 1240-1249.
S47 B. Wang, J. W. Chen, L. Luo, G. K. Huang, Q. Shi, Q. L. Wei, M. H. Shang and Q. Liu, Adv. Funct. Mater., 2025, 35, 2505763.
S48 L. Huang, R. Gao, Y. S. Qiu, J. Zheng, W. J. Zhang, L. R. Zheng, Y. F. Bai, Z. B. Hu, T. R. Zhang and X. F. Liu, Inorg. Chem., 2025, 64, 9703-9714.
S49 J. J. Li, S. Q. Fu, R. J. Wang, K. Sun, W. J. Shi, Y. W. Zeng and B. Zhang, Nat. Commun., 2025, 16, 9910.
S50 H. Chen, P. Liu, W. Li, W. Xu, Y. Wen, S. Zhang, L. Yi, Y. Dai, X. Chen, S. Dai, Z. Tian, L. Chen and Z. Lu, Adv. Mater., 2024, 36, 2411302.
S51 K. P. Wang, M. Wu, Y. Zhang, B. B. Jiang, Y. Q. Su, S. Yang, X. H. Lu and H. Li, Adv. Funct. Mater., 2025, 35,

2424435.

S52 Z. X. Li, Y. C. Yao, S. J. Sun, J. Liang, S. H. Hong, H. Zhang, C. X. Yang, X. F. Zhang, Z. W. Cai, J. Li, Y. C. Ren, Y. S. Luo, D. D. Zheng, X. He, Q. Liu, Y. Wang, F. Gong, X. P. Sun and B. Tang, Angew. Chem. Int. Ed., 2024, 63, e202316522.

S53 X. Kang, F. Yang, Z. Zhang, H. Liu, S. Ge, S. Hu, S. Li, Y. Luo, Q. Yu, Z. Liu, Q. Wang, W. Ren, C. Sun, H.-M. Cheng and B. Liu, Nat. Commun., 2023, 14, 3607.

S54 B. Q. Chen, P. P. Wang, D. Shin, W. Li, T. Y. Liu, M. M. Waegele and D. W. Wang, ACS Catal., 2025, 15, 16476-16482.

S55 A. Malek, L. Wu, Y. Li, C. Y. Li, Y. H. Chen, K. Hazazi, Y. R. Xue and X. Lu, Angew. Chem. Int. Ed., 2026, 65, e20825.

S56 K. Ahanjan, M. Shamsipur and A. Pashabadi, Nanoscale, 2025, 17, 5798-5811.

S57 M. Zhang, Y. Z. Sun, C. C. Meng, Q. J. Xu, Y. Zhang, X. H. Li, L. Z. Fan, T. F. Li and Y. C. Li, J. Mater. Chem. A, 2025, 13, 9886-9898.

S58 Y. Liu, R. Q. Yao, L. B. Chen, T. Y. Dai, X. Y. Sun, S. P. Zeng, Z. L. Zhou, Y. Wang, G. F. Han, T. H. Wang, H. Shi, X. Y. Lang and Q. Jiang, Nano Lett., 2025, 25, 13866-13874.

S59 W.-X. Zheng, X.-X. Cheng, P.-P. Chen, L.-L. Wang, Y. Duan, G.-J. Feng, X.-R. Wang, J.-J. Li, C. Zhang, Z.-Y. Yu and T.-B. Lu, Nat. Commun., 2025, 16, 337.

S60 X. H. Zhang, H. L. Zhang, Z. X. Chen, X. D. Chen, J. Y. Wang, S. X. Wei, S. Y. Liu, Z. J. Wang, F. N. Dai, M. H. Wang and X. Q. Lu, Adv. Funct. Mater., 2025, 35, 2418940.

S61 H. Du, H. Li, J. Song, X. Wang, J. Wang, J. Ma, N. Ran, S. Yu, M. Yang, Y. Jin, J. Liu and J. Wang, Adv. Funct. Mater., 2026, 36, e25265.