

Journal Pre-proof

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PII: S2667-1417(25)00028-X

DOI: <https://doi.org/10.1016/j.esci.2025.100398>

Reference: ESCI 100398

To appear in: *eScience*

Received Date: 8 December 2024

Revised Date: 13 January 2025

Accepted Date: 24 February 2025

Please cite this article as: L. Jiang, L. Jiang, X. Luo, R. Li, Q. Zhou, W. Zeng, J. Yu, L. Chen, S. Mu, External field-assisted catalysis, *eScience*, <https://doi.org/10.1016/j.esci.2025.100398>.

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External field-assisted catalysis

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Abstract

In recent years, substantial effort has been dedicated to improving the intrinsic catalytic activity of catalysts through structural modification, component regulation, and chemical state optimization. However, complexity in the design and construction of catalysts, and the possibility of encountering performance ceilings, may constrain their widespread use. Currently, the introduction of *in situ* external fields, such as force, electric, magnetic, acoustic, light, and thermal fields, is an attractive approach to enhance the catalytic efficiency of catalysts. Such *in situ* physical fields feature continuity, reversibility, and controllability, and can exert external force or energy on catalysts, thereby affecting their microscopic structures and electron arrangements, accelerating their mass transfer and reaction kinetics. Mutual coupling and conversion among different external fields are also worth exploring. Various *in situ* external field effects work in multifaceted ways to promote catalysis in energy-environment systems by optimizing mass/energy transfer processes, modifying structures, and accelerating catalytic reaction kinetics, thereby significantly improving the catalytic properties of materials. This review summarizes and analyzes the latest developments in external field-assisted methods for boosting catalyst performance. The external field effect, related catalysis mechanism, and external field-enhanced catalysis are highlighted, and we discuss future challenges, countermeasures, and opportunities for external field-

assisted catalysis and beyond.

Keywords

Catalysis; External field; Field-assisted effects; Reaction mechanism

1. Introduction

To optimize the world's future energy structure and achieve a low-carbon, low-pollution environment, widespread attention has become focused on utilizing renewable energy and achieving greater levels of environmental protection. Among advanced renewable energy conversion and environmental protection technologies, the catalytic reaction plays a crucial role in increasing conversion efficiencies and reducing carbon emissions [1-6]. For instance, the water electrolysis process features the simultaneous occurrence of the cathodic hydrogen evolution reaction (HER) and the anodic oxygen evolution reaction (OER), both of which are non-spontaneous and have a total theoretical limit potential of 1.23 V. However, due to the high electrochemical potential barrier, electrocatalytic water splitting usually requires a voltage as high as 1.8–2.0 V to proceed [7-10]. Catalysts can promote the reaction kinetics, thereby accelerating the OER and HER by reducing the reactions' overpotential (η). Hence, it is profoundly important to design highly active and stable HER and OER catalysts to achieve water electrolysis with low energy consumption [11-16]. Other catalytic reactions, such as the oxygen reduction reaction (ORR) for fuel cells and metal–air batteries, the hydrogen oxidation reaction (HOR) for fuel cells, the nitrogen reduction reaction (NRR) and carbon dioxide reduction reaction (CO₂RR) for environmental catalysis, and the photocatalysis and thermal catalysis, are also essential for the energy-environment system [17]. In addition, cell reactions, pollutant degradation, desulfurization, denitrification, and air purification play a significant role in energy-environment systems. So for many reasons, we urgently need to rationally design high-

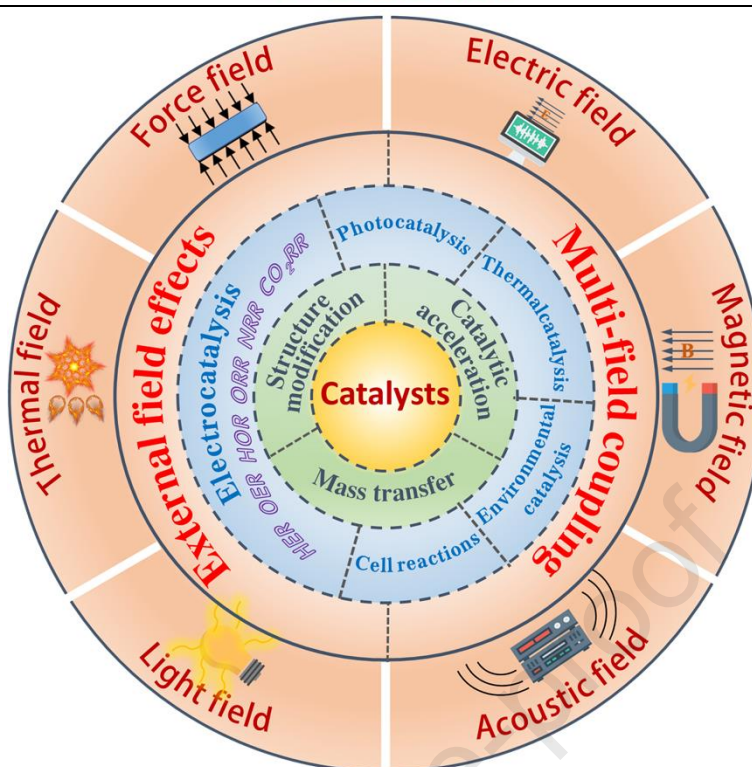
efficiency catalytic systems to meet the requirements of industrial applications for renewable energy storage and conversion as well as environmental protection.

Over the past few decades, great efforts have been made to improve catalyst performance [18-20]. By rationally designing the crystal structure, microscopic morphology, chemical state, electron arrangement, and coordination environment of catalysts, we can boost the intrinsic activity and stability of active sites [21-26]. At present, catalyst performance optimization strategies mainly focus on structural modulation, including morphology modification, crystal phase regulation, defect and phase engineering, co-catalyst deposition, atom doping, and built-in and built-in-outer electric fields; such approaches have been widely used to construct efficient catalysts [27-34]. To obtain novel insights for further improving energy and environment catalysis, we urgently need additional effective methods to optimize catalytic reactions.

Recently, the *in situ* introduction of external fields — such as force, electric, magnetic, acoustic, light, and thermal fields — in catalytic systems has proven effective for enhancing catalytic performance [35-40]. An *in situ* physical field can apply external force or energy to the catalyst, thereby affecting its microscopic structure and electron arrangement and accelerating its mass transfer and reaction kinetics. Different fields also experience mutual coupling and conversion with continuity, reversibility, and controllability [41-45]. Notably, the built-in electromagnetic fields generated by differences in the internal microstructures of catalysts can exhibit pronounced responses under the influence of external fields and significantly affect catalytic performance [46-48]. Field-induced optimization of the catalytic reaction process can be achieved without the need for direct contact with the catalyst, offering an environmentally friendly, simple, and efficient performance enhancement method. However, due to the complex electron transfer process and intermediate

adsorption/desorption mechanism in catalytic processes, the principle of accelerating the catalytic reaction through field-coupled induction is unclear and even controversial [49-54]. Accordingly, it is imperative to understand and apply the process and principle of the *in situ* regulation of catalytic reactions by exerting different external fields. In addition, the combination of field coupling and catalytic mechanism transformation may offer a feasible approach for exploring the structure–effect relationship and the origin of catalysis.

This review therefore aims to investigate and analyze the effects that external fields introduced *in situ* have on electrocatalysis in energy–environment systems (**Scheme 1**). As mentioned above, an external field can be a force, electric, magnetic, acoustic, light, or thermal field or can involve multi-field coupling. *In situ* external fields can exert multifaceted field-assisted effects on catalytic systems to enhance catalytic performance. The review delves into considering the catalytic mechanisms at work under the influence of external fields, including mass transfer, structural modification, and accelerated kinetics. We also briefly review recent research progress on external field-assisted catalysis in other areas, such as photocatalysis, thermocatalysis, cell reactions, and environmental catalysis — including pollutant degradation, desulfurization, denitrification, and air purification. Finally, we summarize the major challenges and possible countermeasures and suggest future development trends for *in situ* field-enhanced catalysis and beyond.



Scheme 1. Schematic of catalytic systems based on external field-assisted catalysis.

2. External field effects and related catalysis mechanisms

External field-assisted catalytic systems are achieved by applying various external fields to the catalytic reactions through multiple physicochemical methods. Hence, the effects of these external fields on catalytic systems and the intrinsic mechanisms of field-assisted enhancement are significant research topics. The improvement of catalytic performance by external field assistance is multifaceted and relates to the catalyst's microstructures, the external field's form of action, and diverse catalytic processes [55-58]. The rational design and utilization of different external field effects can efficiently modify catalytic performance (**Fig. 1**). For example, the introduction of an external force field can lead to lattice distortion, atomic rearrangement, and stress redistribution for the catalyst, thereby optimizing its microstructure, including the density of states, energy band structure, and d-band center [59]. Coupled with the

surface/interface fields of the catalytic process itself, an electromagnetic field can further accelerate electron redistribution and optimize the internal electromagnetic fields, thus enhancing the catalyst's electron conductivity and intermediate adsorption/desorption capability [60]. External acoustic/light fields provide enough energy for electron transition and hole separation during the catalytic process inside the catalyst, thereby accelerating electron transfer and enhancing the material's mass diffusion ability [61]. Thermal fields are closely related to catalytic reactions. As the temperature rises, the catalytic reaction absorbs heat and speeds up; this affects gas diffusion on the catalyst surface and relaxation of the internal nanostructures, which can improve the energy conversion efficiency [62].

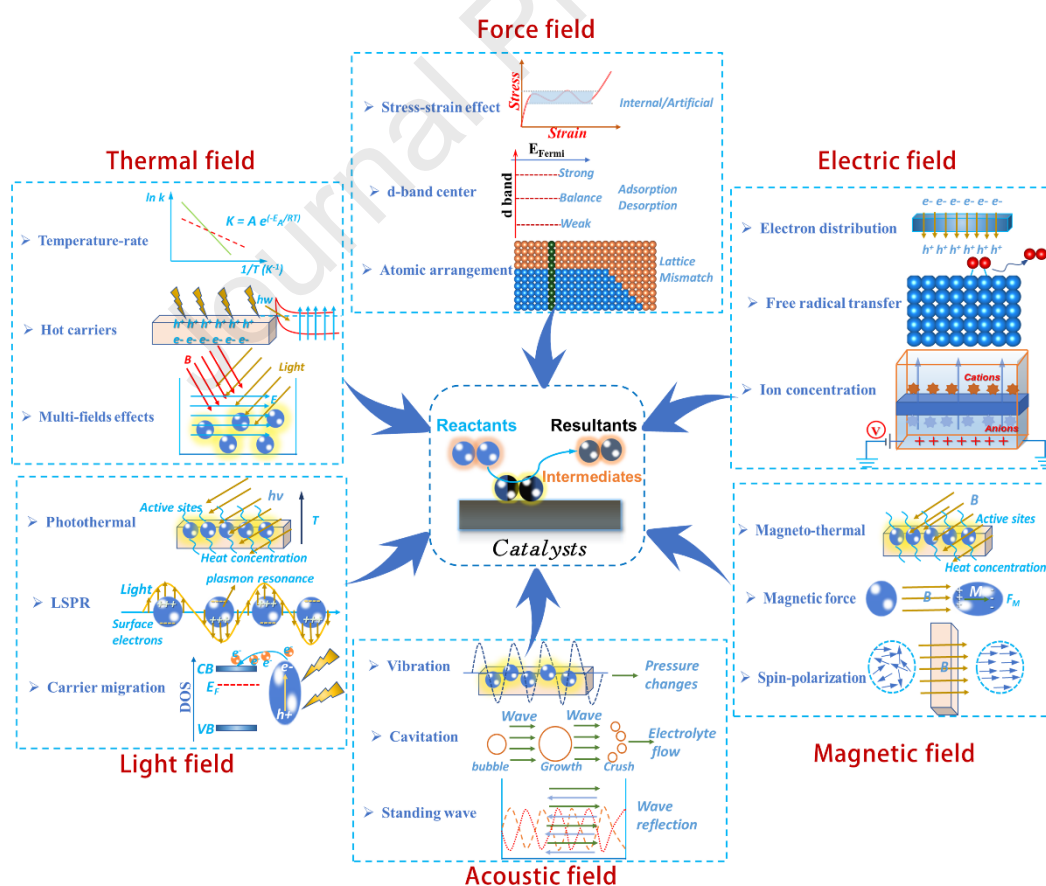


Fig. 1. External field effects on catalysts.

Various external field effects can achieve overall optimization of catalyst structures and catalytic systems. Generally, the introduction of an *in situ* external field cannot only accelerate the macroscopic diffusive mass transfer process but also continuously improve the catalyst's microstructure and charge distribution, thus overcoming the inherent energy scale between the initial state and the transition state and optimizing the catalytic reaction mechanism (**Fig. 2**) [63]. Catalytic reactions usually involve multiple electron transfer paths and interconversion between several transition states, resulting in a complex catalytic mechanism; it is difficult to capture and analyze the intermediate signals, which makes investigating these catalytic mechanisms more difficult. Nevertheless, through non-contact adjustments of field strength and direction, catalytic properties can be correspondingly improved, bringing intrinsic structural modification and the potential for catalytic mechanism transformation. The introduction of external fields thus can be applied to explore catalytic mechanisms and performance enhancement principles during *in situ* catalytic processes, which is conducive to gaining in-depth insights into the corresponding catalytic reaction [64-66].

The principle underlying force-field enhanced catalysis is primarily the optimization and redistribution of the catalyst's electronic structure and atomic arrangement under stress-strain effects (**Fig. 1**). When subjected to an *in situ* external force field, the catalyst undergoes a certain degree of tensile/compressive strain, which improves its atomic spacing, energy band structure, and electronic arrangement. The external force field also leads to an increase in the density of electronic states near the catalyst's Fermi energy level (E_F) and an upward shift of the d-band center, thereby

accelerating electron transfer at the catalytic reaction centers and ultimately improving the catalytic activity (**Fig. 2**) [67,68]. In general, the correlation between stress-strain effects and better catalytic performance can be investigated using mechanical bending, stretching, or compression to apply strain to a catalyst film immobilized on a flexible substrate. Another approach is to improve the stress-strain field within the catalyst by regulating its doping, defects, carrier effects, and lattice mismatches, which can be optimized by coupling external fields to enhance the catalyst's catalytic performance.

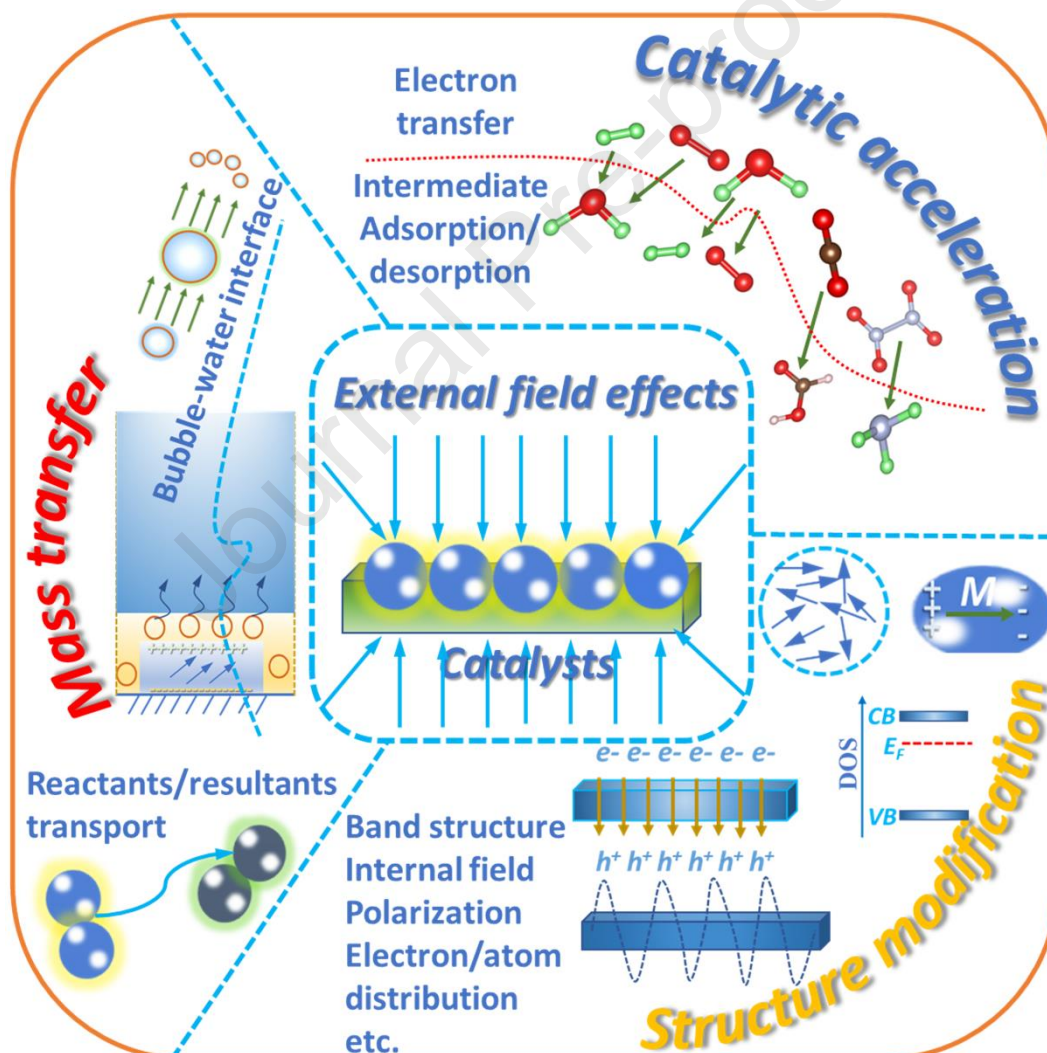


Fig. 2. External field-assisted catalysis mechanisms.

A catalyst's surface electron distribution, free radical adsorption/desorption, and interface ion concentration can be continuously optimized with the assistance of an *in situ* external electric field, leading to accelerated mass transfer and catalytic kinetics (**Fig. 1**) [69]. Unlike structural modulations to achieve built-in electric fields, the application of external electric fields directly influences the overall catalytic system, thereby providing a more straightforward approach to enhancing physicochemical processes [70]. For major semiconductor catalysts, such as MoS₂, CuO, and Fe₃O₄, electrons can accumulate in the catalyst conduction band through capacitive coupling under the effect of perpendicular voltage, which promotes the upward shift of the E_F level and reduces the interfacial contact resistance, thus enhancing the catalytic performance (**Fig. 2**). The adsorption/desorption process of the reaction intermediates is also sensitive to the external electric field. Electron transfer along different paths can be induced when an electric field is applied in different directions, which can regulate the bonding strength between active centers and free radicals and modulate the adsorption energy across a wide range. In addition, the applied electric field can quicken the carrier dynamics at the catalyst/electrode interface, realize the redistribution of interfacial ions, and reduce the contact potential barrier. Usually, electric field-assisted enhanced catalysis can be realized by constructing a gate electrode, field effect transistor, and built-in electric field.

Magnetic field-assisted catalysis is mainly attributed to magneto-thermal, magnetic force, and spin-polarization effects on the catalyst structure and mass transfer process (**Fig. 1**). An external, high-frequency, oscillating magnetic field can induce a strong

magneto-thermal effect, which generates very high localized heat energy near the magnetic catalytic particles, coupling with the thermal field to reduce the apparent activation energy and achieve the favorable self-selective alignment of nanoscale reaction centers. Magnetic forces, including Lorentz and Kelvin forces, acting on magnetic catalysts can induce convection and strain effects, improving the mass transfer kinetics in the diffusion layer [71]. The structure of the spin state of catalysts can also be improved by applying an external magnetic field [72]. Directional alignment and spin-flip reconfiguration are induced to enhance the spin-exchange effect, thus better coupling the active centers with spin-related intermediates and ultimately accelerating the electron transfer process (**Fig. 2**). Furthermore, due to the spin characteristics of oxygen molecules, an external magnetic field can induce rapid O₂ release, thereby accelerating mass transfer under high current conditions. A high-frequency alternating magnetic field can more effectively stimulate a catalyst's local thermal induction and strong spin effects, making magnetic field-assisted catalysis more feasible. Generally, a catalytic system can be assisted by a permanent magnet, a magnetothermometer, or a vibrating sample magnetometer placed close to the working electrode to provide a magnetic field with adjustable intensity and direction.

An external acoustic field can promote electrolyte flow and interfacial mass transfer through the strong vibration effect, cavitation effect, and standing wave effect generated by the acoustic waves (**Fig. 1**). Ultrasonic fields can vibrate the molecules in a medium to produce corresponding pressure changes and eddy current effects, disturbing the electrolyte fluid layer and interface layer and thereby reducing fluid

viscosity and enhancing convective mass transfer. The reactive gas in the electrolyte can be compressed into bubbles under the influence of sound waves and then collapse rapidly, producing strong vortices and eddies, as well as promoting electrolyte mixing and flow [73]. Sound waves can also be reflected off the container to form a local flow field, cleaning the electrode surface and attenuating the corrosion phenomenon in the catalytic process (**Fig. 2**). Generally, the acoustic field-assisted enhancement of catalytic phenomena can be researched by coupling an ultrasonic system with catalytic reactions.

Light as a kind of auxiliary energy can result in the photothermal effect, the localized surface plasmon resonance (LSPR) effect, and a photogenerated carrier migration process, which promote charge transfer and electron leaps and stimulate the activation of catalytic sites, thus improving catalytic activity and selectivity (**Fig. 1**). The light-induced local temperature increases rapidly on the catalyst surface, and concentrated heat near the active sites dramatically improves the reaction rate [74]. When the LSPR effect is generated, metal nanoparticles and free electrons collectively oscillate and resonate with the incident light to optimize the catalyst surface morphology, size, and dielectric structure, while activating the transfer of hot carriers to the lowest unoccupied molecular orbitals (LUMOs) of the adsorbate molecules during radiative decay to improve the strength of the interfacial interactions (**Fig. 2**). During a light-assisted catalytic process, a large number of light-induced carriers will accumulate on the catalyst surface, thereby modifying the density of states (DOS) in the conduction band (CB); this improves catalyst conductivity and ion permeability and

may participate in the redox process to increase the catalyst's intrinsic activity. In general, a light source, a photoabsorber, and a photovoltaic system can be coupled in series with the catalytic system to investigate the phenomenon of *in situ* light field-assisted enhanced catalysis.

Thermal field-assisted catalysis is mainly based on the effect of temperature fluctuation on the reaction kinetics and thermodynamics, including charge transfer at the interface between the electrolyte and the catalytic electrode, the mass transfer diffusion, and the electrode's physical and chemical processes [75]. Thermoelectric coupling can provide a large amount of heat for catalysts, accelerating substance transport and intermediate adsorption/desorption, and thus greatly accelerating the reaction kinetics (**Fig. 1**). A thermal field can also be coupled with other fields, such as light, magnetic, and electric, to produce photothermal, magnetothermal, and electrothermal effects, thereby jointly accelerating the catalytic process (**Fig. 2**). [76] In addition, plasma-induced heat generation arises from relaxation after electron–phonon coupling on the nanoscale, which facilitates the reception of heat energy by the reactive active substances and saves resources.

Inherent connections and transformations are present and occur among various physical fields, thereby making multi-field coupling-assisted catalysis feasible. As mentioned above, electromagnetic fields can polarize molecules/atoms to produce surface stress and strain fields on catalysts, which then interact to improve the catalytic reaction pathways. Additionally, the excitation of thermal fields is an important pathway for multi-field coupling; the inevitable generation of heat by most other external fields acting on the catalytic system works conjointly to accelerate the catalytic

kinetics when the heat is absorbed by the catalyst or reactants. [77] Generally, multi-field coupling-assisted catalysis can be realized by assembling field generators orthogonally or with a certain orientation to couple with the electrochemical system, and the multi-field energy can be efficiently utilized by employing certain coatings/devices with a high degree of multi-field induction effects.

Overall, due to a variety of field-assisted effects and different catalytic reaction mechanisms, investigating the intrinsic principles of external field-assisted catalysis tends to be complex, but it is particularly significant. Considering the consistent reaction processes present in different catalytic systems, including interfacial electron transfer, the adsorption and desorption of intermediates, and the mass diffusion of reactants/resultants, this review focuses on utilizing various external field-assisted effects to optimize catalytic rate, efficiency, and selectivity. In what follows, we will elaborate upon the specific applications of different external fields in various catalytic reactions.

3. External field-enhanced electrocatalysis

3.1. Force fields

External force fields such as compression, gravity, and elasticity can expose materials to stress and strain, which improves catalysts' internal structures and accelerates their electron/mass transfer, thereby optimizing the reaction kinetics. Stress and strain are key parameters that affect the coordination environment and electronic configuration of catalysts. Specifically, the stress-strain effects of a material can optimize the catalyst's d-band center, which is conducive to enhancing the thermodynamic catalytic processes. Nowadays, many studies use external force fields to regulate the stress and strain effects for catalysts, contributing to their structural

modification and performance enhancement. For example, Xue et al. [78] prepared three types of NiOOH by treating NiS₂, NiSe₂, and Ni₅P₄ with a chronopotentiometry method. Different anion reconstruction processes formed different intensities of strain effects, causing octahedral coordination distortion of the NiO₆ in NiOOH and widening the e_g^* band, promoting electron transfer from the catalyst to the external circuit and ultimately improving the catalytic performance (**Figs. 3a and b**). Through a simple and controllable light-induced lattice strain method, Liu et al. [79] synthesized transition metal–organic frameworks (MOFs) to use as dual-function catalysts for the OER and ORR (**Fig. 3c**). Various *in situ* characterization techniques and density functional theory (DFT) calculations revealed the presence of high-valence Ni⁴⁺ catalytic active sites and OOH species, indicating that after *in situ* lattice strain induction, the NiFe MOFs underwent rapid and effective 4e[−] catalytic kinetics. Through *in situ* stress and strain regulation, Hu et al. [80] embedded sub-nanometer Ir clusters into graphene-loaded high-density Ni nanocrystals (Ni-Ir(BCS)/G), realizing bilateral compressive strain at the Ni-Ir interface and thus regulating the reaction and resolution of adsorbed H and OH species (H_{ad} and OH_{ad}). The results showed that Ni and Ir atoms acted as effective synergistic HOR sites to enhance the catalytic performance, and the stable heterogeneous interface ensured long-term durability and CO tolerance (**Fig. 3d**).

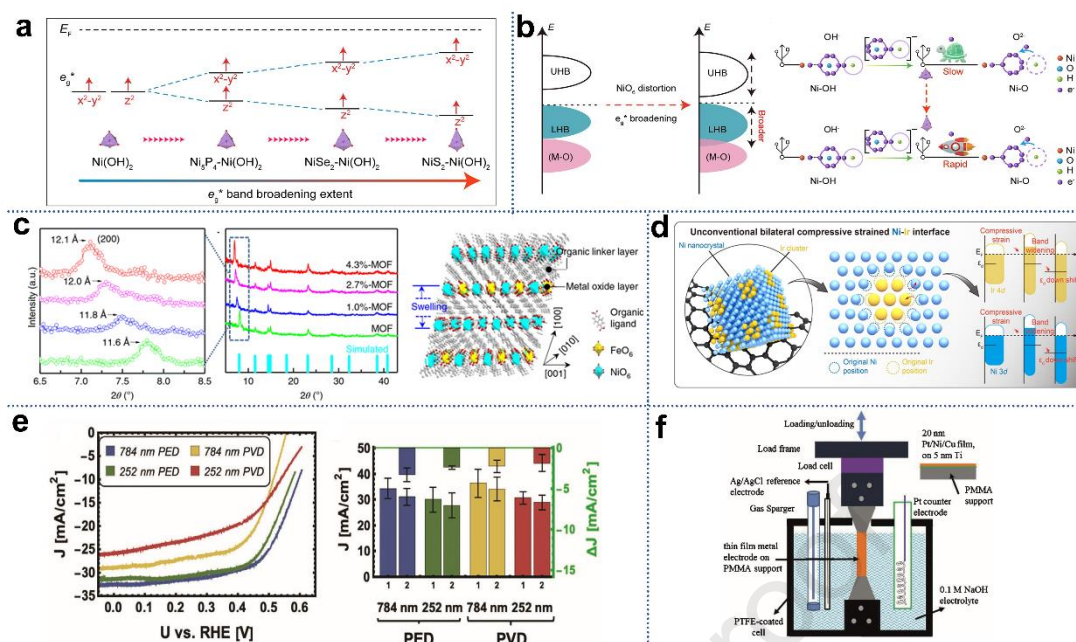


Fig. 3. (a) Schematic diagram of the effect of NiO_6 octahedron distortion on e_g^* band broadening for X-Ni(OH)_2 . (b) The effects of e_g^* band broadening in reconstruction-derived NiOOH on OER activity [78]. Copyright 2023, Royal Society of Chemistry. (c) Structural characterizations of lattice-strained MOFs [79]. Copyright 2019, Springer Nature. (d) Schematic diagram of the bilateral compressive strained Ni-Ir interface in Ni-Ir(BCS)/G and the d-band center shifts [80]. Copyright 2023, American Chemical Society. (e) Chronoamperometric measurements of p-InP photoelectrodes with nanostructured Rh electrocatalyst layers, carried out for 9.2 s in a microgravity environment [81]. Copyright 2022, Wiley-VCH. (f) Experimental setup to subject thin metal films to elastic strain in a universal mechanical testing machine [82]. Copyright 2016, Wiley-VCH.

In addition to inducing internal stress and strain effects in materials, external force fields (gravity/elasticity) can also accelerate bubble overflow, increase interphase slip speed, achieve rapid gas/solid and gas/liquid separation, and then reduce the ohmic resistance and reaction overpotential of materials. For instance, Brinkert et al. [81] explored the photoelectric hydrogen production performance of p-indium phosphide coated with rhodium under a microgravity (10^{-6} g) environment during a 9.2 second freefall process (**Fig. 3e**). They found that the microgravity environment regulated the desorption process of hydrogen gas bubbles, thereby optimizing the catalyst's

photoelectrochemical characteristics. Guduru et al. [82] investigated the effect of externally applied elastic strain on the catalytic activity of metal films during the HER (**Fig. 3f**) and confirmed that external elastic strain can regulate reaction properties in a controllable and continuous manner, consistent with the predictions of the HER volcano plot and d-band center theory. Overall, it is highly meaningful to probe *in situ* force field-induced catalytic acceleration to gain a deeper understanding of catalytic reactions.

3.2. Electric fields

Internal and external electric fields can produce varying degrees of effects on catalysts by inducing electrochemical reactions. External electric fields applied to a catalytic system can couple with the spontaneous built-in electric fields inside the catalyst, jointly accelerating the proton and electron transfer and adsorption/desorption processes and promoting the kinetics of the catalytic reaction. For example, Zhai et al. [83] described exerting an external electric field to adjust the interfacial structure of a CoPc/MoS₂ heterojunction (**Figs. 4a and b**). Theoretical calculations and characterization methods such as *in situ* fluorescence spectroscopy confirmed the transfer of the injected charge (e^-) from CoPc to sulfur vacancies in MoS₂, which enhanced the Mo-H bonding. This modulation altered the CoPc/MoS₂ band gaps and improved interfacial charge accumulation, thereby accelerating the HER catalytic kinetics. Wang et al. [84] proposed an electric field treatment strategy to enhance the conductivity and catalytic activity of Ni/Co₃O₄ thin films (**Figs. 4c and d**). They discovered that after treatment with an external electric field, the oxides manifested directionally aligned oxygen vacancies, and then conductive channels in the catalyst

films formed *in situ*, thereby promoting rapid charge migration and effectively performing overall water splitting.

External electric field-assisted electrocatalysis can improve the energy conversion pathways of traditional anode and cathode catalytic reactions, which is conducive to improving catalytic efficiency. Song et al. [85] utilized additional weak currents to enhance the nitrate (NO_x) reduction performance of vanadium-based catalysts. They investigated the *in situ* application of weak electric currents and its augmentative effect on the redox stages of the catalytic process. Their central finding indicated that the external current weakened the V–O chemical bonds and activated the molecular oxygen within the catalyst, thereby improving the conversion efficiency of nitrogen oxides (**Fig. 4e**). Mai et al. [86] fabricated field-tuned HER devices using individual MoS_2 nanosheets to explore the influence of external electric fields on catalysis. When a back-gate voltage of 5 V was applied, the Tafel slope was halved, and the overpotential decreased from 240 to 38 mV (**Fig. 4f**). Clearly, the introduction of the external electric field optimized the channel conductivity of the device in conjunction with the band structure and charge transfer capabilities of the MoS_2 crystals, significantly enhancing the catalytic performance. Subsequently, Mai et al. [87] probed the structural and performance changes of MnO_2 nanowire catalysts in the OER process using an *in situ* external electric field-assisted strategy. As shown in **Figs. 4g–i**, deprotonation and proton coupling were enhanced, maintaining a moderate adsorption energy of the key intermediate OOH at Mn–Mn dual sites, facilitating proton–electron cooperative transfer, and eventually improving the electrochemical performance of MnO_2 .

External electric fields can also induce surface/interface ion concentration regulation, thus altering the thermodynamic and kinetic properties of elementary catalytic reactions. Ding et al. [88] efficiently regulated the electrochemical performance of single-atom catalysts/2D crystals through a directed external electric field system (**Fig. 4j**). They discovered that the external electric field induced charge accumulation near the single-atom active sites and the enrichment of reactant ions at the interface of the 2D crystals and the electrolyte; these effects polarized the frontier orbitals of metal atoms/adsorbates/intermediates, thereby significantly enhancing the catalytic reaction pathway. As shown in **Fig. 4k**, Mai et al. [89] investigated the optimization principles of back-gate voltage on the HER catalytic kinetics. The *in situ* application of back-gate voltage induced ion redistribution at the interface between the electrolyte and the VSe₂ nanosheets catalyst, leading to an accumulation of more reactants and charges, which accelerated the adsorption/desorption kinetics of intermediates and thus greatly improved the intrinsic catalytic activity. Generally, by constructing different forms of *in situ* external electric fields during the electrocatalytic reaction process, the electronic arrangement of a catalyst's surface structure and the adsorption of intermediates can be improved, thereby accelerating the catalytic reaction process.

The built-in electric fields in catalysts can also be continuously modulated through *in situ* external fields; this is conducive to electronic distribution and interfacial charge transfer during the catalysis process and is being widely investigated for enhancing heterostructure/heterojunction catalyst performance. Under the influence of the

external electric field, the built-in electric field is regulated due to the existence of heterogeneous interfaces with different electronic configurations and band structures inside the catalyst. The strong interaction between the internal and external electric fields can effectively improve the spatial charge distribution on the catalyst surface/interface, thereby optimizing the adsorption/desorption behavior of reaction intermediates. For example, Cui et al. [90] designed hetero-nano structures of $\text{Ni}_5\text{P}_4/\text{Ni}_3(\text{BO}_3)_2$ with different internal electric field directions and utilized their local opposite electric fields at the interface to effectively control hydrogen adsorption and H_2 desorption, thereby promoting efficient hydrogen evolution (**Fig. 4l**). Our group [91] synthesized the heterostructure Os/OsSe_2 by a molten salt-assisted method under the guidance of DFT calculations. It was found that the two different crystal structures spontaneously formed an in-built electric field at the heterogeneous interface, which induced charge transfer and equilibrium between the two phases, resulting in a bidirectional optimization of hydrogen adsorption energy (ΔG_{H^*}) and exhibiting better HER activity than commercial Pt catalysts (**Figs. 4m and n**). Subsequently, we [47] investigated the HER performance of a heterostructure composed of amorphous oxide-supported PdRu in a five-fold twinned structure based on work function theory (PdRu-MOx). They discovered that due to symmetry breaking and strong interfacial interactions, the catalyst established a pronounced spontaneous built-in-outer electric field, which optimized the proton adsorption and bubble evolution processes. Consequently, it exhibited remarkable catalytic activity and stability in alkaline media.

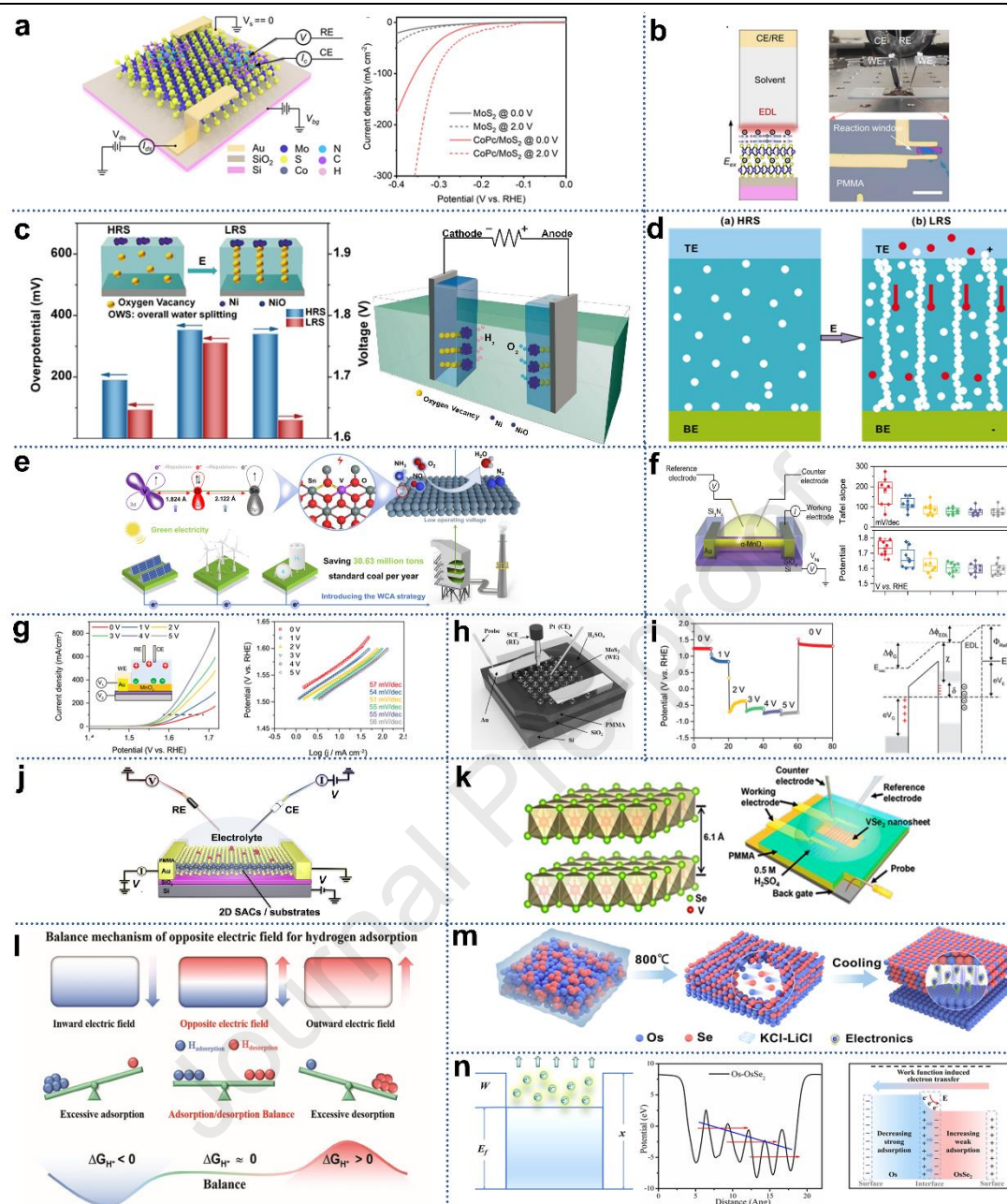


Fig. 4. (a) Schematic of the electrical and back-gate dependent measurement of the electrochemical device, and the polarization curves of MoS₂ and CoPc immersion devices from 0 V (solid) to 2 V (dash). (b) Different views of the CoPc/MoS₂ device [83]. Copyright 2022, Wiley-VCH. (c) Schematic diagram of the mechanism of LRS sample as a bifunctional electrocatalyst for overall water splitting, and the corresponding overpotentials. (d) Schematic diagram of the resistance switching (RS) mechanism: high resistance state (HRS) and low resistance state (LRS) [84]. Copyright 2022, Springer Singapore. (e) Schematic diagram of current-assisted catalysis and prospects for catalyst electrification [85]. Copyright 2024, Springer Nature. (f) Schematic diagram of three electrodes for HER catalytic measurement, and HER polarization curves at different back-gate voltages [86]. Copyright 2017, Wiley-VCH. (g-i) Electrochemical performance of the single α -MnO₂ nanowire device [87]. Copyright 2024, Springer Nature. (j) Schematic illustration of *in situ*

electronic/electrochemical investigations on Pt SACs/MoS₂ for HER under oriented external electric field regulation [88]. Copyright 2022, Springer Nature. (k) Schematic of the catalysts and HER device. 0.5 M H₂SO₄ was used as the HER electrolyte. Heavily doped silicon (gray) is used as the back-gate source, and 300 nm SiO₂ (ocher) is used as the gate dielectric. Such devices enable easy control of different back-gate voltages [89]. Copyright 2017, American Chemical Society. (l) Characteristics of hydrogen adsorption and desorption in outward electric field, inward electric field, and the opposite electric field, based on the crystal symmetry [90]. Copyright 2023, Wiley-VCH. (m) Schematic illustration of the fabrication of Os-OsSe₂. (n) Work function and charge transfer process of Os/OsSe₂ [91]. Copyright 2022, Wiley-VCH.

3.3. Magnetic fields

The magnetic domain structure, spin alignment, and unpaired electron characteristics of catalysts can be enhanced with an external magnetic field, which can accelerate the spin-dependent catalytic kinetics and promote the progression of catalytic reactions. In particular, for a ferromagnetic catalyst toward the OER/ORR, the ground spin state of the reactants OH⁻/H₂O is a singlet with all electrons paired, whereas the product O₂ is in a triplet ground state with two parallel electrons occupying the frontier π^* orbitals. It has been reported that the singlet energy level of oxygen molecules is at least ~1 eV higher than the triplet state [92]. Therefore, the use of magnetic field effects to modify and enhance spin polarization is theoretically feasible for optimizing OER/ORR catalysts [93-95]. For instance, Xu et al. [96] prepared NiFe thin films with thicknesses ranging from 200 to 800 nm using magnetron sputtering. These films had stripe-like magnetic domains with adjacent domains magnetized antiparallel (**Fig. 5a**). When an external magnetic field was applied, domain walls gradually disappeared, and the NiFe film electrodes evolved into a single-domain state. The researchers attributed the enhanced OER performance under the magnetic field to the disappearance of

domain walls and the increase in domain size. Ding et al. [97] reported a carbon-based magnetic nanocage catalyst, in which simply applying a moderate magnetic field could directly enhance the oxygen electrocatalytic activity (**Fig. 5b**). They found that the external magnetic field magnetized cobalt (Co) into a nanomagnet with high spin polarization, promoting the adsorption of oxygen intermediates and electron transfer and significantly improving the catalytic efficiency. Wu et al. [98] embedded ferromagnetic Ni nanoparticles into a nitrogen-doped carbon matrix to investigate the enhancement of CO₂ reduction performance under an external magnetic field (**Fig. 5c**). Characterization and computational results demonstrated that the external magnetic field induced the disappearance of magnetic domain walls and the formation of ordered magnetic moments, which strengthened the Ni–O–Ni interactions and lowered the energy barrier of the COOH* intermediates, ultimately enhancing the catalytic efficiency. Gao et al. [99] investigated the enhanced oxygen catalytic activity of FeCo₂O₄ nanofibers under *in situ* external magnetic field assistance. By applying an external 1 T magnetic field, they found the optimal 3d–2p spin hybridization process and regulated the charge transfer dynamics in FeCo₂O₄ catalysts, resulting in strong interactions between the magnetic Fe/Co atoms and the O atoms. This improvement facilitated the adsorption and transfer of oxygen-containing intermediates, thereby significantly enhancing the catalytic performance.

Utilizing electromagnetic induction and spin polarization effects is a very promising strategy for achieving electrocatalysis reactions. For example, Yan et al. [100] synthesized crystalline Fe-DABDT and Co-DABDT and optimized the effective

magnetic moments to explore the role of spin magnetic effects in regulating water oxidation activity (**Fig. 5d**). Experiments and DFT calculations showed that magnetized Fe sites can facilitate nucleophilic reactions, accelerate the polarization of electron spin states, and ultimately promote the polar decomposition of OH and the formation of O–O bonds. Xu et al. [101] prepared a high-performance CoFe oxygen/hydroxide system (**Fig. 5e**). Under the spin pinning effect, brief magnetization by the magnetic field promoted the oxygen spin polarization, further enhancing electrocatalytic activity. Their research unveiled that the stable oxide/hydroxide surface produced a strong pinning effect, which accelerated the transfer of 2p electrons of specific spin-up/down reactant oxygen species in the catalyst. This resulted in the formation of oxygen species with parallel spin alignment, thus promoting the formation of triplet state oxygen. Xue et al. [102] also built a high-spin state Co^{3+} CoOOH structure by introducing coordination-unsaturated Co atoms where electron transfer occurs in the vertex-to-vertex e_g^* orbitals, exhibiting faster electron transfer capabilities (**Fig. 5f**).

Utilizing alternating magnetic fields to enhance electrochemical performance is another important method in magnetic field-assisted catalysis. Liu et al. [103] proposed a magnetic-stimulation strategy to improve the OER performance of a CoMn-based MOF catalyst with a superlattice feature. Under the continuous influence of an external alternating magnetic field, their thermally driven spintronic catalyst $\text{Co}_{0.8}\text{Mn}_{0.2}$ MOF achieved localized heating and spin restructuring. The alternating field also modulated the orbital interactions of spin-related intermediates, realizing high OER catalytic activity and stability. Overall, magnetic field-enhanced OER reaction kinetics and spin-

induced rapid electron transfer are effective methods for achieving field-assisted enhancement of catalytic reactions. Undoubtedly, further investigation of the interaction between spin polarization and the OER mechanism will support the rational design of efficient and stable catalysts.

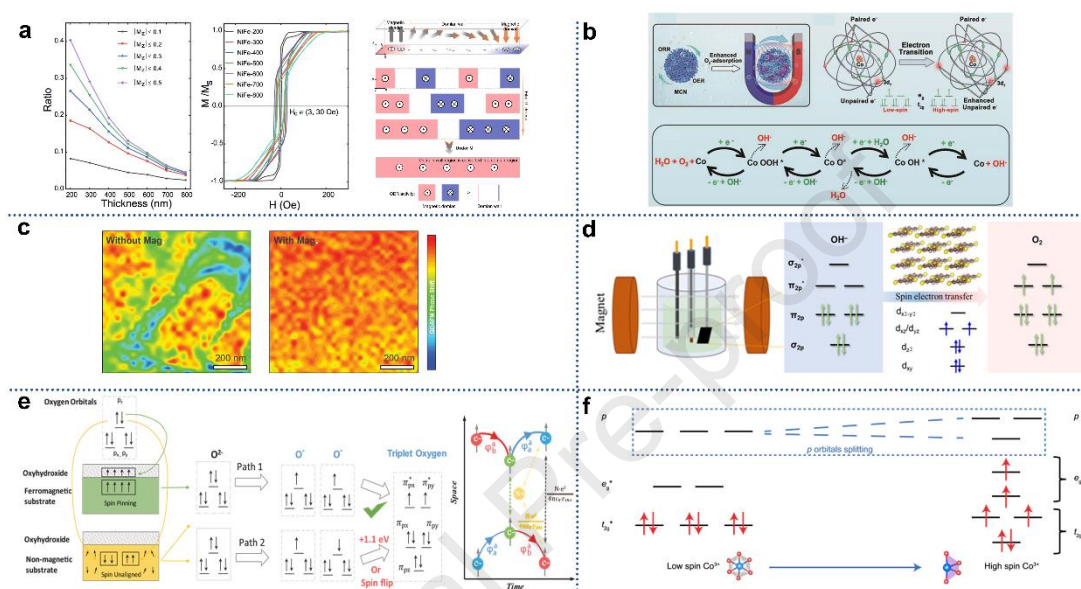


Fig. 5. (a) The origin of magnetization-induced increments in the OER of NiFe films [96]. Copyright 2023, Springer Nature. (b) Illustration of implementing magnetic enhancement in the ORR and OER of Co magnetic catalytic nanocages [97]. Copyright 2021, Wiley-VCH. (c) QDAFM image recorded above a Ni@NC catalyst while operating a NV magnetometer in iso-B imaging mode [98]. Copyright 2024, Wiley-VCH. (d) Schematic of OER test equipment for applying an external magnetic field to an Fe-DABDT catalyst, and illustration of O–H dissociation acceleration.[100] Copyright 2024, American Chemical Society. (e) Spin pinning effect for triplet oxygen evolution on tCoFe oxyhydroxide [101]. Copyright 2021, Springer Nature. (f) Configure of 3d and 4p orbitals for low-spin state Co³⁺ in R-CoOOH and high-spin state Co³⁺ in S-CoOOH [102]. Copyright 2024, Springer Nature.

3.4. Acoustic fields

As a conventional method, ultrasonication has been widely used to enhance mass transfer in physicochemical processes. The catalytic process involves strong interactions between the electrode and the electrolyte, encompassing phenomena such as catalyst attachment, mass transfer, and bubble diffusion. The *in situ* application of an

external acoustic field during catalytic processes is beneficial for activating and cleaning the electrode surface, bubble detachment and overflow, and mass and energy transfer between the catalyst and the electrolyte [104]. For instance, Yeo et al. [105] investigated how high-frequency (10 MHz) mixed acoustic waves enhanced the HER performance of an Au electrode in a neutral electrolyte (**Figs. 6a and b**). They found that under ultrasonication, Au electrode corrosion and ohmic resistance in the electrochemical process were reduced, bubble diffusion was accelerated, and the hydrogen-bonding coordination network of interfacial water was disrupted, allowing free water molecules to adsorb more easily onto the electrode surface. Pollet et al. [106] designed a simple strategy to boost the OER activity of metal Ni surfaces in an alkaline media with ultrasound (24 kHz, 44 W) (**Fig. 6c**); they concluded that the enhancement was due to the rapid bursting and spilling of bubbles, as well as secondary sonochemical reactions at the electrode/electrolyte interface.

Ultrasonication can produce certain piezoelectric effects, thereby forming an intrinsic electric field and dipole structure in the catalyst, which is conducive to the separation and transfer of electrons and holes. For example, Zhang et al. [107] utilized localized surface plasmon resonance sonication to promote the internal electron transfer and external mass transfer processes of Au@MoS₂, accelerating O-H bond breakage in water molecules and active hydroxyl species and thereby optimizing the HER reaction process and energy conversion efficiency (**Fig. 6d**). Tang et al. [108] evidenced the feasibility of enhancing the catalytic performance in lithium–oxygen batteries through ultrasound. Under high-power ultrasonic charging assistance, the concentration

polarization of the battery was mitigated, which enhanced mass transport and facilitated the rapid decomposition of discharge products (Li_2O_2), thereby optimizing the kinetics of the OER and ORR, as well as improving the battery's cycling stability (Figs. 6e and f). External acoustic fields are beneficial for improving the mass and energy transformation processes between the substance and the environment and then accelerating the redox reactions on the catalyst surface. A deep understanding of how to apply *in situ* acoustic fields in catalytic systems will be conducive to the rational design of highly efficient and stable catalysts.

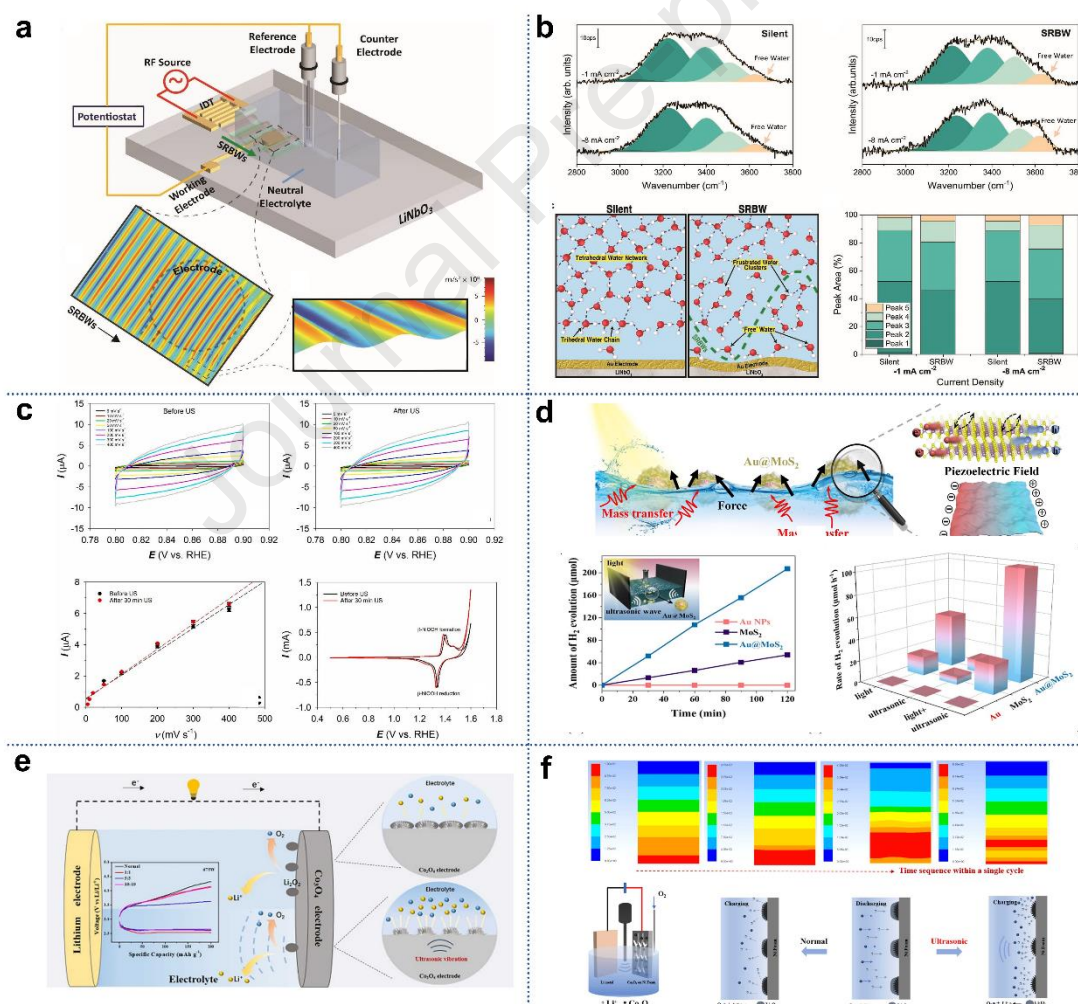


Fig. 6. (a) Schematic depiction (not to scale) of a surface-reflected bulk waves (SRBW) electrochemical cell. (b) Interfacial water state at the electrode–electrolyte interface under silent conditions and SRBW excitation [105]. Copyright 2023, Wiley-VCH. (c)

Cyclic voltammetry (CV) scans of a Ni(poly) electrode in 1.0 M KOH solution at different scan rates before and after ultrasonication for 30 min [106]. Copyright 2022, Elsevier. (d) Schematic of the mass-transfer and piezoelectric effects from water waves under an ultrasound field, and the amounts of hydrogen produced from samples in different conditions [107]. Copyright 2022, American Chemical Society. (e) The illustration of ultrasonic-assisted enhancement of lithium-oxygen battery performance. (f) Distribution diagram of fluid simulation under ultrasonic fields, and scheme of the ultrasonic charging mechanism on the electrode surface [108]. Copyright 2022, Elsevier.

3.5. Light fields

Light-assisted catalysis has become a promising frontier of catalytic research in recent years. For example, compared with pure water electrolysis, external light field-induced catalysis has the advantages of multiple energy conversion pathways and accelerated reaction kinetics. Photo-responsive catalysis can produce photo-generated carriers directly involved in redox reactions, as well as enough energy to accelerate electron transfer and reduce the catalytic barrier, thereby optimizing the catalyst's microstructure and performance. Piccinin et al. [109] used transient photocurrent measurements to reveal the high degree of dependence between the OER rate of hematite Fe_2O_3 and the density of surface photo-generated holes (**Figs. 7a and b**). They uncovered a dependence relationship between the size of the photocurrent and the charge stored on the surface of the catalyst. When the photocurrent was enhanced, the photo-generated holes promoted the single-electron proton-coupled electron transfer step and accelerated the deprotonation of OH, thus reducing the apparent activation energy. Huang et al. [110] immobilized the photosensitive donor $\text{Ru}(\text{bpy})_3\text{Cl}_2$ within a cobalt porphyrin-based covalent organic framework (COF) to investigate its enhanced catalytic performance for CO_2 reduction with external light field stimulation. Under illumination, photoexcited electrons continuously transferred from the ruthenium-

based donor to the cobalt-based COF acceptor, resulting in the formation of a substantial built-in electric field (**Fig. 7c**). This significantly prolonged the excited-state lifetime of the cobalt porphyrin, ultimately enhancing the Faradaic efficiency and partial current density for CO production.

Under continuous light induction, the microscopic electronic structure and coordination environment of a catalyst will change, thereby optimizing the catalytic reaction kinetics. For example, Xue et al. [111] reported a light-induced switchable and optimized electron transfer route where electron transfer occurred through the lowest available energy pathway (**Fig. 7d**). The light-triggered coupled oxygen evolution mechanism (COM) involved the crystal structure undergoing reversible geometric conversion between octahedral (NiO_6) and square planar (NiO_4) to obtain electronic states with alternating metal and oxygen characteristics throughout the oxygen evolution process. Under light induction, metals and oxygen states acted jointly as redox centers, bypassed traditional potential-limiting steps, and had good universality. The photoelectric energy conversion efficiency of the COM mechanism was thereby increased. Xue et al. [112] also explored the regulatory effect of Fe doping on coordination distortion in NiO_6 (**Figs. 7e and f**), demonstrating that Fe doping led to different degrees of e_g^* band broadening. A larger degree of broadening was beneficial to accelerate OH deprotonation, which increased the non-overlapping area of the d_{z^2} orbit and the a_{1g} orbit. Fe promoted the transfer of electrons from the M–O orbit to the empty d_{z^2} orbit, improved photon utilization, and ultimately showed higher OER activity.

Gaining a deep understanding of how to apply photogenerated hot carriers is also crucial for enhancing the catalytic process through the LSPR effects generated by external light fields. For instance, Qiu et al. [113] utilized the enhanced plasmonic response of two-dimensional MXenes to improve their electrocatalytic activity (**Fig. 7g**). Under visible/near-infrared light irradiation, MXenes induced strong photothermal conversion and simultaneous hot electron effects in a prolonged sub-femtosecond to picosecond timescale, which significantly reduced the endothermic enthalpy and activation energy for the HER, thus enhancing the hydrogen production performance more than fivefold. Jiang et al. [114] reported that plasmonic promotion caused a redistribution of thermal electrons among the surface atoms in Au₃Cu alloy nanoparticles, which enhanced the electrocatalytic NRR (**Fig. 7h**). Under simulated sunlight, a significant LSPR effect was generated on the Au atom surface, exciting more hot electrons to Cu atoms, which triggered interatomic electron regulation and increased NH₃ desorption, thereby resulting in approximately 93.9% greater ammonia yield.

In conclusion, using light fields to enhance catalytic reactions is a non-contact, environmentally friendly method conducive to sustainable development. Combining light induction with the electrocatalytic reaction mechanism can help researchers better understand and design energy and environment catalysts.

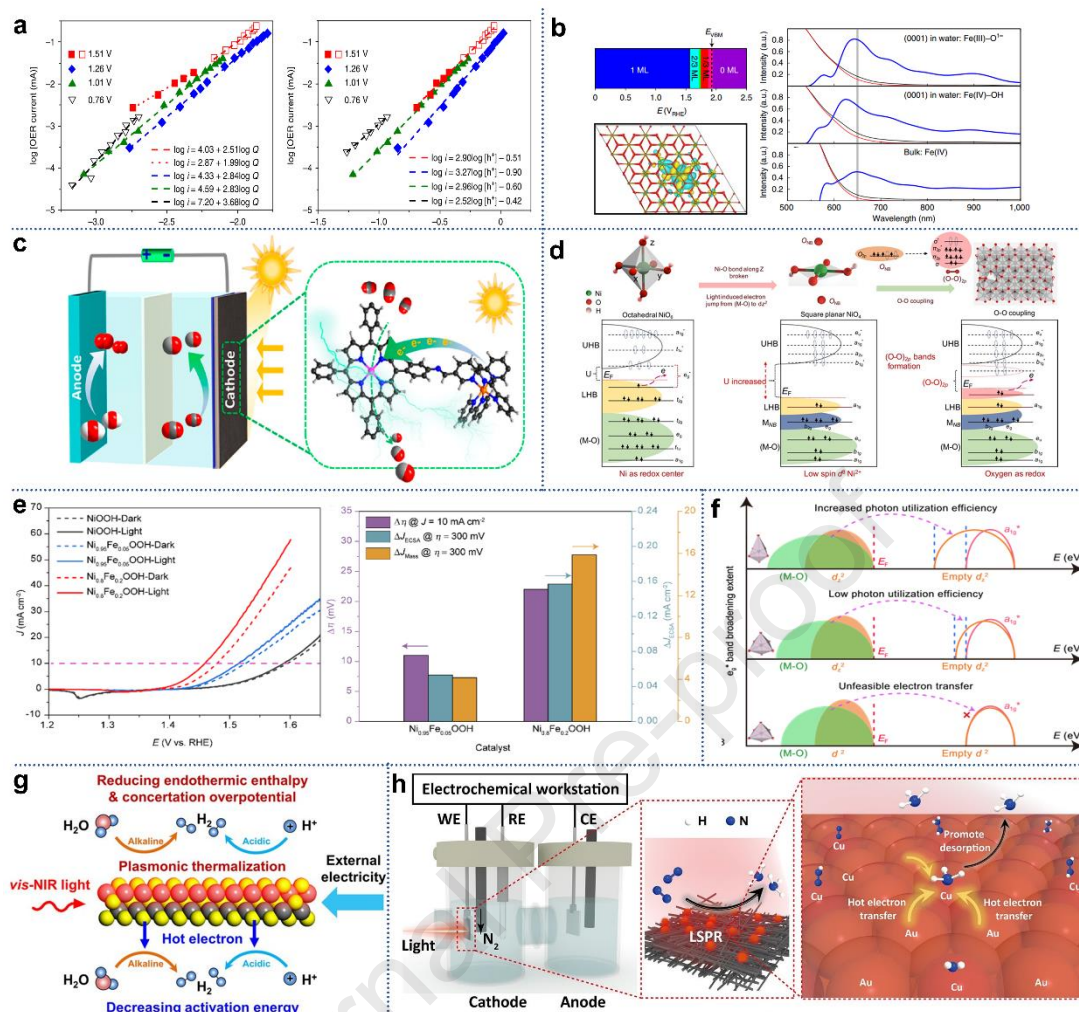


Fig. 7. (a) Mechanistic analysis of water oxidation on hematite. (b) Theoretical optical absorption fingerprints of surface holes [109]. Copyright 2022, Springer Nature. (c) Proposed schematic mechanism for the photocoupled electrocatalytic CO_2RR on Co-Bpy-COF- $\text{Ru}_{1/2}$ [110]. Copyright 2023, American Chemical Society. (d) Proposed light-induced electron transfer process with switchable metal and oxygen redox centers for the OER. Schematic illustration of OER routes induced by light fields [111]. Copyright 2022, Springer Nature. (e) Electrochemical characterization of $\text{Ni}_{1-x}\text{Fe}_x\text{OOH}$ for the OER under dark and light conditions. (f) Schematic illustration of the effects of e_g^* band broadening on facilitating electron transfer from (M-O) to empty d_{z^2} by the COM route [112]. Copyright 2023, Springer Nature. (g) Schematic illustration of the LSPR-induced photothermal and hot-electron effect to improve the electrocatalytic HER performance of MXenes [113]. Copyright 2021, Wiley-VCH. (h) Schematic design and conjectured mechanism of the plasmon-mediated electrocatalytic NRR [114]. Copyright 2024, Wiley-VCH.

3.6. Thermal fields

Temperature is an important parameter affecting the thermodynamics and kinetics of chemical reactions. In fact, catalysts need to overcome the activation energy barrier during the catalytic reaction process, allowing reactant molecules to adsorb and products to desorb from the surface. The reaction rate of this process follows a linear Arrhenius relationship with reaction temperature, $k = A \times \exp(-E_a/RT)$, where k is the reaction rate constant, A is the pre-exponential factor, E_a is the activation energy, R is the ideal gas constant, and T is the reaction temperature. Under normal circumstances, increasing the reaction temperature increases the energy obtained by the reactants, making it easier to overcome the activation energy barrier and thus accelerating the reaction rate. However, a high reaction temperature can lead to catalyst deactivation, electrolyte loss, and other issues, so an appropriate *in situ* thermal field-coupled catalytic reaction is an effective method for enhancing catalytic performance and energy conversion efficiency. For example, Wu et al. [115] proposed a self-circulating electrochemical thermal OER mechanism (SET-OER) (**Figs. 8a and b**) and revealed that the catalyst underwent two consecutive reactions at the anode: first, Ni(OH)_2 was electrochemically oxidized to NiOOH , and then NiOOH was thermally decomposed *in situ* to Ni(OH)_2 and released oxygen. Compared to the traditional four-electron OER, the SET-OER reaction had a lower energy barrier and exhibited higher catalytic activity. Wang et al. [116] achieved the efficient production of high-purity hydrogen and carbon monoxide by coupling thermocatalytic methanol dehydrogenation with electrocatalytic hydrogen oxidation on a bifunctional Ru/C catalyst (**Figs. 8c and d**). This coupling reduced the partial pressure of hydrogen, optimized the chemical equilibrium of

methanol dehydrogenation, and facilitated the cleavage of C–H bonds, thereby enhancing the methanol conversion efficiency and the HOR rate.

A thermal field acting on materials can produce certain thermalphysical effects, such as thermal diffusion, thermal expansion, and thermal phase transition, thereby improving catalyst structure and optimizing reaction kinetics. For example, Yan et al. [117] found that a thermal field induced a compressive strain effect on the IrO₆ octahedra in the anisotropic thermal expansion material Sr₂IrO₄ (**Fig. 8e**). Under the introduction of an external thermal field, the Ir d band center shifted downward, optimizing the intermediate binding strength of Ir active species and accelerating the OER kinetics in a non-linear Arrhenius relationship. This process was reversible. Li et al. [118] cascaded thermal catalysis and water electrolysis to achieve a qualitative leap in OER energy conversion efficiency (**Fig. 8f**). They demonstrated that the thermal field activated the direct coupling of *O and *OH on the Fe sites to form high-energy *OOH, resulting in significantly enhanced activity at a high temperature. Yu et al. [119] designed a thermally enhanced electrocatalytic system to investigate the modification effects of single-atom alloy oxides on the NO₃RR. Under the assistance of an external thermal field, a high concentration of reactive hydrogen species was generated at the Ni sites with strong proton affinity, which facilitated the subsequent hydrogenation–reduction reactions of NO_x* adsorbed on the copper surface, thereby significantly enhancing the rate and efficiency of ammonia production (**Figs. 8g and h**). In general, heat is a common and convenient energy source. Using a thermal field to regulate the catalytic process is an effective and promising strategy that helps deepen our

understanding of the mechanisms governing external field-enhanced catalytic performance.

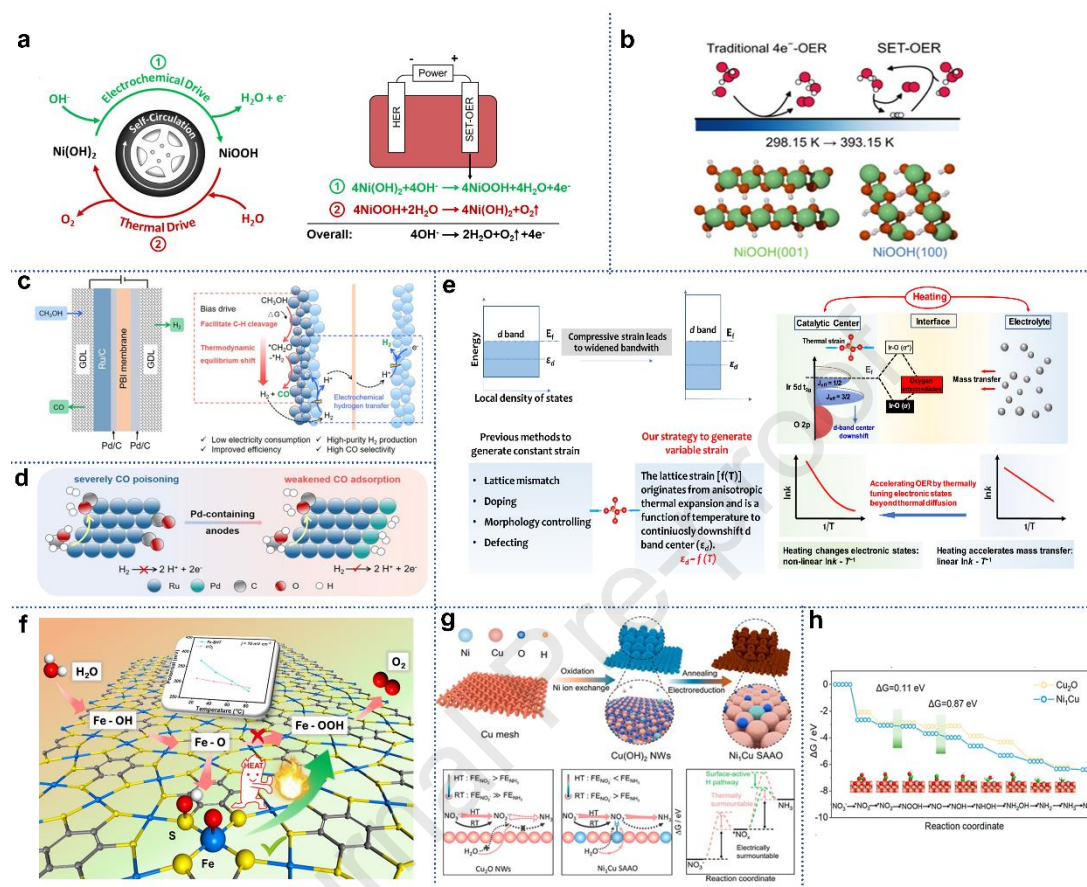


Fig. 8. (a) Schematics of the SET-OER mechanism. (b) Schematic of the traditional 4e^- -OER and the SET-OER; atomic structures of $\text{NiOOH}(001)$ and $\text{NiOOH}(100)$. [115]. Copyright 2023, Royal Society of Chemistry. (c) Sketch of the thermal electrochemically coupled catalytic process. (d) Schematic illustration of how CO poisoning on Pd-containing anodes is alleviated [116]. Copyright 2024, American Chemical Society. (e) Energetics at catalyst-electrolyte interface with a thermal strain effect.[117] Copyright 2024, Springer Nature. (f) Illustration of thermally activated combination of *O and *OH on the surface of ironbenzenehexathiol coordination polymer [118]. Copyright 2021, American Chemical Society. (g) Schematic of Ni_1Cu SAAO catalyst preparation and how the energy barrier for nitrate reduction is surmounted by thermally enhanced electrocatalysis. (h) Gibbs free-energy diagram of nitrate reduction to ammonia and water dissociation on Cu_2O and Ni_1Cu [119]. Copyright 2024, American Chemical Society.

3.7. Multi-field coupling

Multi-field coupling to accelerate catalytic reactions is also a current research hotspot. By integrating the synergistic effects among various external fields, it is possible to provide greater energy and driving force to a catalytic system. This inter-coupling of field effects facilitates further kinetic modification and enhances energy conversion efficiency. For example, Qin et al. [120] enhanced the OER performance of $\text{Co}_3\text{O}_4/\text{CoFe}_2\text{O}_4@\text{NF}$ under the synergistic action of light, thermal, and magnetic fields (**Fig. 9a**). They found that Co_3O_4 reduced resistance under the thermal field, CoFe_2O_4 underwent electron polarization under the light–magnetic field, and oxygen atoms were arranged in parallel, thereby enhancing the OER reaction kinetics. Xu et al. [121] established a magneto-mechanical coupling system based on magnetostrictive and piezoelectric catalysis to assist the OER and ORR processes in lithium–oxygen batteries (**Figs. 9b and c**). Under the influence of an external magnetic field, a $\text{CoFe}_2\text{O}_4/\text{BiFeO}_3$ (CFO/BFO) catalyst generated magnetostrictive stress, while the built-in electric field produced by the piezoelectric effect facilitated electron–hole transport, thereby accelerating the kinetics of the anode and cathode reactions and reducing the charge–discharge overpotential.

Combining the thermal field with other external fields to enhance catalytic reactions is also a current research hotspot [122]. For example, Liu et al. [123] selected the thermoelectric material NaNbO_3 to investigate its coupled auxiliary photoelectrocatalytic performance for water splitting under the influence of magnetic and thermal fields (**Figs. 9d and e**). They found that the magnetic field yielded limited enhancement of the photocatalytic performance. However, the thermomagnetic effect

generated under the combined action of the magnetic and thermal fields overcame the limitations imposed by the magnetically controlled non-radiative recombination of charge carriers, resulting in a significant increase in the photocathode current density. Yan et al. [124] reported a thermally induced magnetic transformation strategy to accelerate the rate of redox reactions (**Fig. 9f**) and demonstrated that heating a NiFeO_xH_y catalyst to a Curie temperature above 70 °C caused a change in the ferromagnetic-paramagnetic spin state of $\text{Ni}^{2+}/\text{Ni}^{3+}$, sharply reducing the activation energy of redox and ultimately accelerating the thermoelectric coupling and OER kinetics. Lin et al. [125] investigated the photothermal effects of NiFe_2O_4 spinel nanoparticles (NFO NPs) and analyzed the principles of this enhanced OER performance through DFT calculations and *in situ* characterization. They observed that under near-infrared illumination, the temperature of NFO NPs gradually increased, which accelerated the formation of NiFe oxyhydroxides at a lower voltage, thereby reducing the activation energy barrier and promoting the generation of highly active surface species. Catalytic systems assisted by multi-field coupling generate various advantageous field effects that are conducive to transcending the performance enhancement limits of a single field through strong interactions [126]. This presents a significant direction for future research and development in field-assisted catalytic processes.

Overall, there has been extensive, in-depth research on external field-assisted electrocatalysis. Under the influence of external fields, electrocatalytic performance has been improved to varying degrees (**Table 1**). This review primarily focuses on work

conducted in various catalysis fields, with the expectation that these findings can be widely applied across different catalytic and synthetic domains in energy–environment systems.

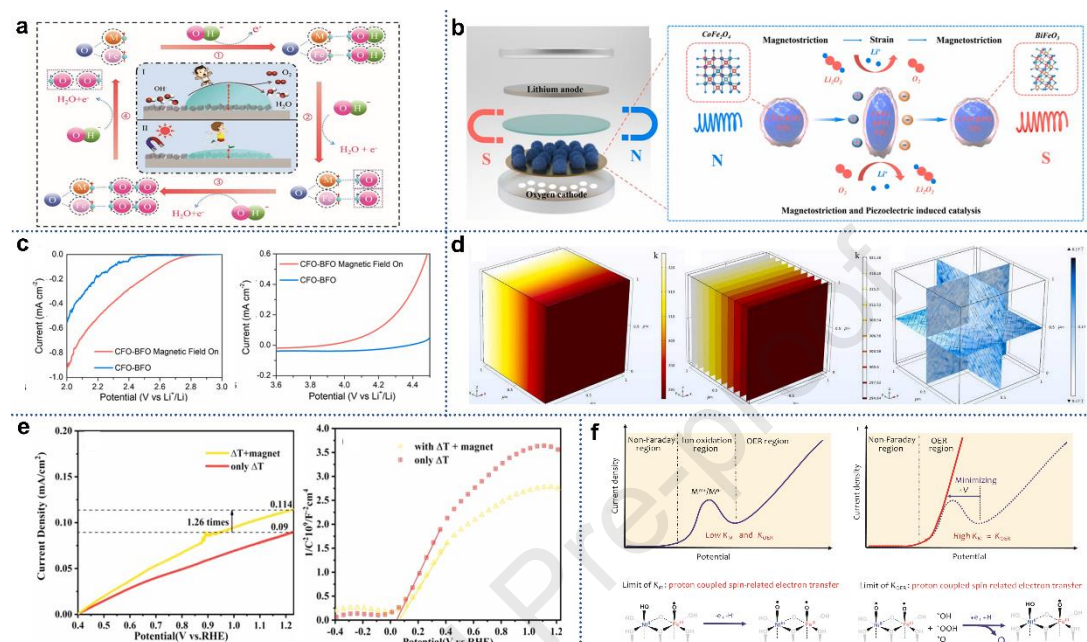


Fig. 9. (a) Spin-polarization mechanism of the OER under photothermal–magnetic fields [120]. Copyright 2023, Wiley-VCH. (b) Schematic of piezoelectric catalysis mechanism for Li-O₂ batteries based on magnetostriction and piezoelectricity. (c) ORR and OER processes with/without magnetic field at a scan rate of 5 mV s⁻¹ [121]. Copyright 2024, Elsevier. (d) Combined application of multiple physical fields (magnetic and thermal) to NaNbO₃ (1 × 1 × 1 μm), simulated by COMSOL. (e) Current density versus applied potential (I-V) curves of NaNbO₃ under thermal and magnetic fields [123]. Copyright 2023, Elsevier. (f) The main kinetic obstacles in redox couple-mediated water splitting [124]. Copyright 2022, Wiley-VCH.

Table 1. Summary of external field-enhanced electrocatalysis.

External Fields	Catalysts	Reactions	Performance (Initial)	Performance (Field-assisted)	Ref.
Force	NiS ₂ -NiOOH	OER	343 mV at 10 mA cm ⁻²	241 mV at 10 mA cm ⁻²	[78]
	NiFe MOF	OER/ORR	600 mV at 200 mA cm ⁻²	210 mV at 200 mA cm ⁻²	[79]
	Ni-Ir(BCS)/G	HOR	1.6 mA cm ⁻² at 50 mV	2.1 mA cm ⁻² at 50 mV	[80]
	p-InP	HER	27.8 mA cm ⁻² at -0.09 V	42.6 mA cm ⁻² at -0.09 V	[81]
	Pt films	HER	184 mV at -1 mA cm ⁻²	176 mV at -1 mA cm ⁻²	[82]
	(CoPc)/MoS ₂	HER	238 mV at 10 mA cm ⁻²	180 mV at 10 mA cm ⁻²	[83]
	Ni/Co ₃ O ₄	HER/OER	190/353 mV at 10 mA cm ⁻²	93/311 mV at 10 mA cm ⁻²	[84]

Electric	Nb-VO _x	NRR	TOF = $0.76 \times 10^{-3} \text{ s}^{-1}$	TOF = $4.04 \times 10^{-3} \text{ s}^{-1}$	[85]
	MoS ₂	HER	240 mV at 100 mA cm ⁻²	38 mV at 100 mA cm ⁻²	[86]
	MnO ₂	OER	440 mV at 100 mA cm ⁻²	360 mV at 100 mA cm ⁻²	[87]
	Pt SACs-MoS ₂	HER	123 mV at 25 mA cm ⁻²	71 mV at 25 mA cm ⁻²	[88]
	VSe ₂	HER	126 mV at 10 mA cm ⁻²	70 mV at 10 mA cm ⁻²	[89]
	B-Ni ₃ P ₄	HER	111 mV at 10 mA cm ⁻²	33 mV at 10 mA cm ⁻²	[90]
	Os/OsSe ₂	HER	83 mV at 10 mA cm ⁻²	26 mV at 10 mA cm ⁻²	[91]
	PdRu@MO _x	HER	186 mV at 1000 mA cm ⁻²	110 mV at 1000 mA cm ⁻²	[47]
Magnetic	NiFe films	OER	331 mV at 10 mA cm ⁻²	318 mV at 10 mA cm ⁻²	[96]
	Co-MCN	OER	436 mV at 10 mA cm ⁻²	421 mV at 10 mA cm ⁻²	[97]
	Ni@NC	CO ₂ RR	$j_{\text{CO}} = -5.9 \text{ mA cm}^{-2}$ at -1.0 V	$j_{\text{CO}} = -24.3 \text{ mA cm}^{-2}$ at -1.0 V	[98]
	FeMn/NC	OER/ORR	350 mV at 10 mA cm ⁻²	310 mV at 10 mA cm ⁻²	[99]
	Fe-DABDT	OER	320 mV at 10 mA cm ⁻²	306 mV at 10 mA cm ⁻²	[100]
	CoFeO _x H _y	OER	311 mV at 10 mA cm ⁻²	297 mV at 10 mA cm ⁻²	[101]
	S-CoOOH	OER	374 mV at 10 mA cm ⁻²	226 mV at 10 mA cm ⁻²	[102]
	Co _{0.8} Mn _{0.2} MOF	OER	$3514.7 \text{ A g}_{\text{metal}}^{-1}$ at 0.27 V	$166.6 \text{ A g}_{\text{metal}}^{-1}$ at 0.27 V	[103]
Acoustic	PC Au	HER	0.92 V at 10 mA cm ⁻²	0.40 V at 10 mA cm ⁻²	[105]
	Ni(poly)	OER	387 mV at 10 mA cm ⁻²	364 mV at 10 mA cm ⁻²	[106]
	Au@MoS ₂	HER	100 $\mu\text{mol H}_2$ at 120 min	207 $\mu\text{mol H}_2$ at 120 min	[107]
	Co ₃ O ₄ /NF	OER/ORR	0.883 V at 400 mAh g ⁻¹	0.883 V at 400 mAh g ⁻¹	[108]
Light	α -Fe ₂ O ₃	OER	0.21 eV of APP energy	0.18 eV of APP energy	[109]
	CoB _{py} -COF-Ru	CO ₂ RR	$j_{\text{CO}} = -11.93 \text{ mA cm}^{-2}$ at -1.0 V	$j_{\text{CO}} = -16.27 \text{ mA cm}^{-2}$ at -1.0 V	[110]
	NR-NiOOH	OER	182 mV at 10 mA cm ⁻²	147 mV at 10 mA cm ⁻²	[111]
	Fe-NiOOH	OER	236 mV at 10 mA cm ⁻²	215 mV at 10 mA cm ⁻²	[112]
	Au ₃ Cu alloy	NRR	$27.17 \mu\text{g h}^{-1} \text{ mg}^{-1} \text{ NH}_3$ at 0.3 V	$31.73 \mu\text{g h}^{-1} \text{ mg}^{-1} \text{ NH}_3$ at 0.3 V	[113]
	Ti ₃ C ₂ T _x MXene	HER	578 mV at 10 mA cm ⁻²	128 mV at 10 mA cm ⁻²	[114]
	MnWO/FCN/Ti	HER/OER	HER: 104 mV at 10 mA cm ⁻² OER: 234 mV at 10 mA cm ⁻²	HER: 64 mV at 10 mA cm ⁻² OER: 204 mV at 10 mA cm ⁻²	[127]
Thermal	NiOOH/NF	OER	290 mV at 10 mA cm ⁻²	100 mV at 10 mA cm ⁻²	[115]
	Ru-Pd/C	HOR	$558.54 \text{ mmol h}^{-1} \text{ g}^{-1} \text{ H}_2$	$199.6 \text{ mmol h}^{-1} \text{ g}^{-1} \text{ H}_2$	[116]
	Sr ₂ IrO ₄	OER	312 mV at 10 mA cm ⁻²	235 mV at 10 mA cm ⁻²	[117]
	Fe-BHT	OER	372 mV at 10 mA cm ⁻²	282 mV at 10 mA cm ⁻²	[118]
	NiCu-SAAO	NRR	$1.6 \text{ mg h}^{-1} \text{ cm}^{-2} \text{ NH}_3$ at 0.1 V	$9.7 \text{ mg h}^{-1} \text{ cm}^{-2} \text{ NH}_3$ at 0.1 V	[119]
Multi-field	Co ₃ O ₄ /CoFe ₂ O ₄	OER	248.9 mV at 10 mA cm ⁻²	172.4 mV at 10 mA cm ⁻²	[120]
	CFO/BFO	OER/ORR	charging platform of 4.11 V	charging platform of 3.49 V	[121]
	NaNbO ₃	HER/OER	0.14 mA at 1.23 V	0.45 mA at 1.23 V	[123]
	NiFeO _x H _y	OER	310 mV at 10 mA cm ⁻²	221 mV at 100 mA cm ⁻²	[124]

Cu ₂ S/MoS ₂ /Pt	HER	289 mV at 10 mA cm ⁻²	78 mV at 10 mA cm ⁻²	[128]
NiFe ₂ O ₄	OER	307 mV at 20 mA cm ⁻²	272 mV at 20 mA cm ⁻²	[125]

4. Other catalysis with external field assistance

To date, there has been systematic progress in theoretical research and practical application scenarios related to *in situ* external field-assisted electrocatalysis. External field-assisted enhancement strategies have also demonstrated broad research potential in other energy- and environment-related fields, including photocatalysis, thermocatalysis, lithium batteries, supercapacitors, pollutant degradation, desulfurization, denitrification, and air purification [129-134]. External field-assisted photocatalysis is an important research hotspot [60,65,135-137]. For instance, Lin et al. [138] sandwiched a layer of the photothermal material Co₃O₄ between a BiVO₄ photoanode film and an FeOOH/NiOOH electrocatalyst to investigate thermal field-assisted enhancement of its photocatalysis water splitting performance (**Fig. 10a**). They found that the Co₃O₄ layer exhibited a significant photothermal effect under near-infrared irradiation, which increased the reaction temperature *in situ*, thus prolonging the light absorption time, enhancing the charge transfer, and ultimately accelerating the water oxidation kinetics. Lin et al. [139] also explored the performance-enhancing effect of thermoelectric field-assisted photocatalytic disinfection (**Figs. 10b and c**). By synergistically compounding pyroelectric materials with a typical photocatalyst, the temperature fluctuation generated by the photothermal effect was utilized to promote photoexcited carrier separation and transfer, which resulted in a more than 95% improvement in antimicrobial performance. Applying different external field effects to

a photocatalytic system can effectively improve the ability of photogenerated carriers to separate and transfer, which accelerates charge/mass transfer and significantly enhances the catalytic performance.

For thermocatalysis, Zhang et al. [140] developed an electromagnetic field (EMF)-assisted Haber–Bosch method utilizing commercial iron-based catalysts for ammonia synthesis under mild conditions (**Fig. 10d**). Under the EMF, more electrons could transfer from the d orbitals of Fe to the N–N orbitals, thereby facilitating the adsorption and activation of inert N₂, which reduced the initial temperature for synthesis and enhanced the ammonia yield. Wang et al. [141] coupled the photothermal material MnCo₂O₄ with Ru nanocatalysts, employing *in situ* light-field coupling to assist the thermocatalytic hydrogenation of CO₂ to methane. Under the influence of the external light field, the local temperature of the Ru nanoparticles increased sharply, while the photogenerated electron transfer process enhanced the CO₂ conversion rate, ultimately reducing the reaction temperature and improving methane selectivity.

As far as lithium battery reactions are concerned, Li et al. [142] investigated the catalytic enhancement mechanism of transition-metal compounds for sulfur redox in lithium–sulfur batteries (LSBs) (**Fig. 10e**). They achieved p-band center modulation and interfacial charge rearrangement through Mo-doped VS₂/MXene heterostructures. The built-in electric fields between the heterogeneous components simultaneously optimized the charge and discharge processes, thereby accelerating electron transfer and leading to the accumulation of electrons at the surface sulfur sites. Through synergistically decreasing the reaction energy barriers for polysulfide reduction and

Li₂S oxidation, they ultimately improved the initial capacity and cycling performance of LSBs. Li et al. [143] researched the magnetic field-enhanced polysulfide capture mechanism to mitigate the intrinsic dissolution/shuttle effect of lithium–sulfur compounds. Fe/Fe₃C/graphene nanocatalysts became effective sulfur hosts under the action of an external magnetic field, increasing sulfur loading and accommodation volume, promoting fast electron transfer and sulfur conversion kinetics, and thus reducing polysulfide dissolution.

In the case of supercapacitors, Z. Zhang et al. [144] achieved light field-assisted catalysis to enhance the energy density of all-solid-state supercapacitors (ASSD) (**Fig. 10f**). They fabricated a typical Co₃O₄/g-C₃N₄ p-n junction (CoCN), which significantly improved the electrochemical performance by leveraging the advantages of light energy absorption, light-induced built-in electric field formation, and charge carrier separation under light irradiation. At a current density of 26.6 mA cm⁻², photoirradiation enhanced the capacity of their CoCN/CoCN ASSD device by 70.6%, demonstrating the potential application of photo-assisted catalytic effects in supercapacitors for energy conversion and storage, such as photoelectrochemical, photothermal, and photogenerated carrier migration.

For desulfurization and denitrification reactions, Zhou et al. [145] investigated the degradation effects of desulfurization oxidants under ultrasonic treatment (**Fig. 10g**). They found that ultrasound facilitated the mixing of water and oil, and the resultant localized high temperature and pressure enhanced the oxidative capacity of the desulfurization agents, accelerating the generation of free radicals and reactive oxygen

species and ultimately improving the desulfurization efficiency. Wu et al. [146] examined the impact of magnetic field coupling on the nitrogen removal efficiency of wetland plants and microbial communities (**Fig. 10h**). Under a magnetic field (average 110 mT), the abundance of nitrifying bacteria increased significantly, which in turn enhanced the activity of microbial enzymes, thereby intensifying the nitrification processes within the constructed wetlands and effectively treating nitrogen pollutants in wastewater.

Regarding pollutant degradation, Wang et al. [147] prepared a membrane catalyst, CdS/TiO₂-ferroelectric PVDF, characterized by a large surface area and high pollutant capture capacity (**Fig. 10i**). Under the influence of external light excitation and piezoelectric polarization, the membrane achieved simultaneous degradation of Cr⁶⁺, methylene blue, and bisphenol A, maintaining stable water purification activity after 20 recovery cycles. Pané et al. [148] reported the catalytic degradation of organic compounds utilizing the magnetoelectric properties of CoFe₂O₄-BiFeO₃ (CFO-BFO) core-shell nanoparticles (**Figs. 10j–l**). With the assistance of an external alternating magnetic field, they observed a certain modulation of the piezoelectric response, which facilitated the polarization of BFO and generated local surface charges that reacted with surrounding water and oxygen to form superoxide species, thereby driving the degradation of organic pollutants.

Investigating air purification, Kim et al. [149] utilized an externally enhanced local electric field generated by nanowires to disrupt the structures of microbes. Specifically, they assembled a disinfection system driven by a triboelectric nanogenerator, which

prompted microbial transport and current enhancement, thereby accelerating the catalytic deactivation of bacterial viruses and achieving high air disinfection efficiency.

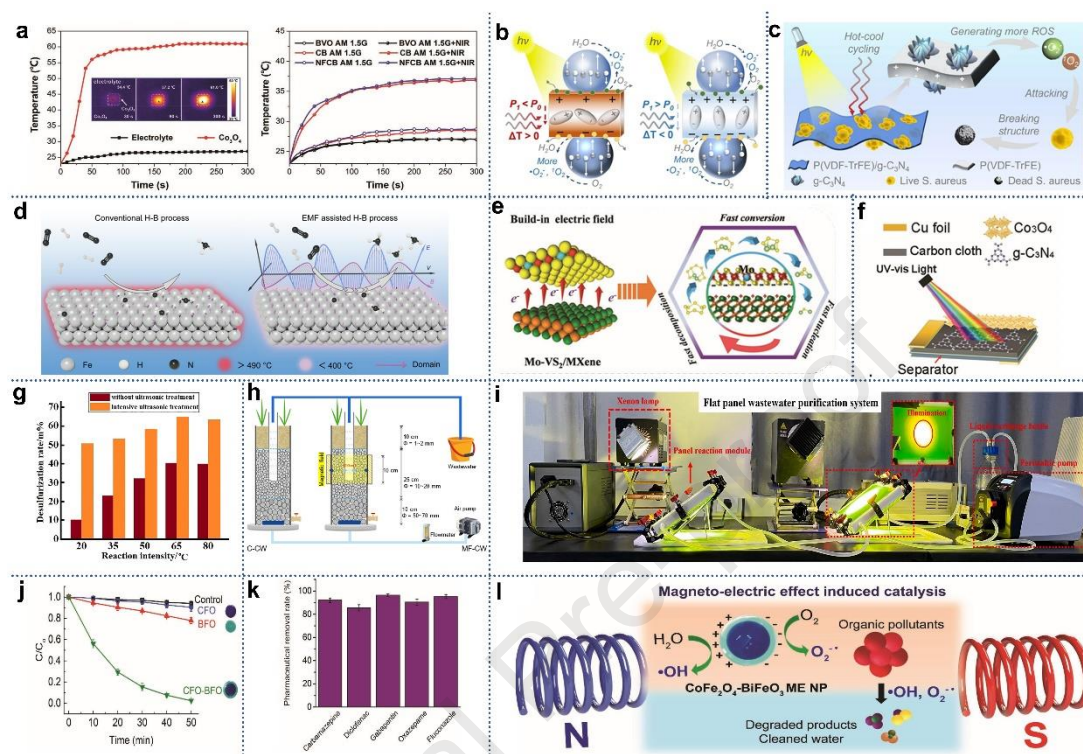


Fig. 10. (a) Time-dependent temperature variations of Co_3O_4 and electrolyte solution [138]. Copyright 2021, Wiley-VCH. (b) Schematic illustration of the pyro-phototropic effect on photocatalytic disinfection performance. (c) Schematic diagram of pyro-phototropic effect-enhanced photocatalytic disinfection of composite film under light illumination and temperature fluctuation [139]. Copyright 2024, American Chemical Society. (d) Schematic illustration of the EMF assistance principle and equipment for thermocatalyzed NH_3 synthesis [140]. Copyright 2023, Elsevier. (e) The $\text{Mo-VS}_2/\text{MXene}$ catalyst and built-in electric fields for LSBs [142]. Copyright 2024, Wiley-VCH. (f) Schematic diagram of photocatalysis-assisted all-solid-state $\text{CoCN}//\text{CoCN}$ flexible devices [144]. Copyright 2020, Wiley-VCH. (g) Effect of ultrasound-assisted oxidation desulfurization at different temperatures [145]. Copyright 2020, Elsevier. (h) Schematic diagram of experimental constructed wetlands systems with and without magnetic field [146]. Copyright 2022, Elsevier. (i) Panel wastewater purification system using $\text{CdS}/\text{TiO}_2\text{-PVDF}$ [147]. Copyright 2024, Elsevier. (j) Catalytic degradation curves for model organic dye, RhB, under 15 mT and 1 kHz magnetic fields. (k) Removal efficiency for five common pharmaceuticals using core-shell NPs ($n = 4$). (l) Scheme of magnetoelectric effect-induced catalytic degradation of organic pollutants using core-shell CFO-BFO NPs under magnetic fields [148]. Copyright 2019, Wiley-VCH.

5. Challenges and responses

External field-assisted catalysis plays a pivotal role in energy and environmental systems. Nowadays, theories of external field-assisted effects and related catalytic mechanisms have been systematically recognized and studied, and have also found practical applications and promotion in various research areas. However, despite significant progress, our understanding of the intrinsic principles of external fields' effects and the sophisticated mechanisms underpinning the synergistic catalysis of external field-enhanced catalytic reactions are still in the early stages and require substantial further exploration.

1) The influence of external fields on catalysts is multifaceted. It is necessary to study the pleiotropic effects of the collaborative processes during external field application and reaction performance. For example, a light field can produce a photothermal effect on certain materials and can combine with the electronic effect of photogenerated carriers to further reduce reaction resistance and accelerate a catalytic reaction. A strong magnetic field can cause structural changes in ferromagnetic materials, generating corresponding stress-strain effects to optimize the material structure. Hence, more accurate and comprehensive characterization and testing methods are needed to further investigate the multiple effects of single external field-assisted catalysis.

2) The synergistic effects of multi-field coupling need to be further investigated. *In situ* multi-field coupling can be multifunctionally applied to catalytic systems to improve their overall performance. However, it is relatively difficult to achieve performance-enhancing effects in catalysts under multiple external fields. The

implementation of multi-field coupling auxiliary strategies involves the meticulous simulation and design of catalyst structures. Therefore, the principles underlying the synergy between different fields, such as the piezoelectric effect, magnetostrictive effect, and photoelectric effect, require in-depth research and application to the interactions between catalysts and external fields. It is also necessary to design efficient and suitable external field-coupling systems to explore the effects of multi-field coupling on catalysts.

3) The energy utilization efficiency of external field-assisted catalytic systems needs to be considered. External field-assisted catalysis to improve catalytic performance is a recognized method. However, compared to pure catalysis, external field induction usually requires another form of energy for conversion and storage, inevitably reducing energy utilization efficiency. Achieving higher energy utilization efficiency in externally assisted catalytic reactions is therefore an urgent aim. When using external fields, it is essential to carefully consider the various energy utilization rates and conversion efficiencies in order to achieve high catalytic activity with low energy consumption. Strategies to improve energy utilization efficiency include enhancing the responsiveness of the catalyst to external fields, *in situ* external field coupling through the exploitation of green renewable energy, and recovering excess energy.

4) The application of various *in situ* characterization methods and theoretical calculations should be emphasized. External fields are mostly introduced into the catalytic reaction system *in situ* to accelerate reaction kinetics. Therefore, the use of

various *in situ* characterization and measurement methods enables researchers to observe and monitor the precise modification processes occurring in the microstructures and chemical states of catalysts under *in situ* external fields. Theoretical calculations, artificial intelligence, machine learning, and big data modeling can also provide a deeper understanding of the principles of external field-enhanced catalysis.

5) Researchers should investigate the combination of external field induction with catalytic reaction mechanisms. Currently, exploring the catalytic reaction mechanism to rationally design catalysts is the mainstream research method. The enhanced effect of external fields on catalytic reactions may originate from acceleration of the electron transfer process, optimization of the intermediate adsorption/desorption pathways, and transformation of the reaction mechanisms. It is thus promising to use external fields to enhance catalytic reaction efficiency from the perspective of catalytic mechanisms. Through the study of catalytic modification under *in situ* field-effect conditions, new insights into catalytic mechanisms and multi-electron reaction processes can be attained.

6) To better investigate how external fields enhance catalytic performance, it is imperative to propose novel, efficient external field-assisted methods. Currently, the introduction of external fields varies widely according to different field effects. However, most approaches are relatively complex and require precise coupling with catalytic systems. Furthermore, due to the interconnections and conversions among different physical fields, conducting research on single field effects becomes quite intricate. For instance, UV illumination of a catalytic system inevitably raises the overall temperature and exerts additional influences on catalytic performance, thereby

hindering in-depth research on catalysis assisted solely by a light field. Consequently, there is a pressing need to develop sophisticated instruments and equipment to conduct detailed analyses of the field effects in catalytic processes.

7) The feasibility of introducing external fields under actual industrial conditions requires exploration. To achieve the sustainable development of energy and environmental systems, more concise and efficient catalytic performance enhancement needs to be developed. Currently, how external fields and catalysis systems are coupled is unsuitable for industrial conditions that require large-scale preparation and popularization. Moreover, industrial electrolysis conditions are more demanding, which may hinder the actions of external fields and the reception of their energy by catalysts. Therefore, the development of low-energy, easily prepared, efficient, and stable external field-assisted catalytic systems is a major challenge that needs to be investigated and addressed.

6. Summary and outlook

In summary, the *in situ* introduction of external fields to catalysis systems is an interesting and promising strategy to enhance the overall catalytic performance of catalysts. Herein, we have summarized current research progress on external field-assisted catalytic systems, including external field effects, catalytic mechanism analyses, structural regulation, cutting-edge applications, as well as future challenges and prospects. The synergistic regulation of various external fields is an effective method to improve mass transfer, electronic distribution, and catalytic reaction thermodynamics/kinetics, significantly enhancing catalytic efficiency. Specifically,

external fields can accelerate surface electron transfer and bubble overflow by applying force/energy/intensity to the catalyst, and can also regulate *in situ* the structure and electronic properties of a catalyst to optimize its reaction pathway, ultimately improving the overall catalytic performance. Multi-field coupling-assisted catalytic reactions can further enhance intrinsic activity and stability while also providing new insights into basic physicochemical principles and novel design approaches for overall catalytic systems. We have identified the key issues for external field-assisted catalysis and have suggested countermeasures, with a view to promoting its wider application and the achievement of new breakthroughs in external field auxiliary strategies for energy–environment catalysis.

In future, external field-assisted strategies that are efficient and environmentally friendly can be increasingly applied in the areas of energy conversion, environmental protection, and other fields. By coupling the design of material structures with external field interactions, catalysts' responses to external fields and the structural modification process can be remarkably enhanced, thereby improving overall performance. In addition, *in situ* performance modification through external fields is beneficial for investigating complex reaction mechanisms, including multi-electron transfer pathways and the processes of intermediate binding. Finally, interdisciplinary efforts involving advanced methods of introducing external fields, *in situ* characterization techniques, and systematic structural design are anticipated to achieve more efficient, tunable, low-carbon, and low-energy-consumption external field-enhanced catalytic systems. We believe that external field-assisted catalysis strategies open new avenues for energy

conversion and storage, environmental protection and remediation, as well as physicochemical synthesis. We therefore hope this review provides readers with deeper insights into the fundamental research and integrated applications of external field-assisted strategies in catalysis and beyond.

Acknowledgments

This work was financially sponsored by the National Natural Science Foundation of China (Grant Nos. 22179104, 22379117), and the State Key Laboratory of Advanced Technology for Materials Synthesis and Processing (Wuhan University of Technology) (2023-ZT-1).

Competing financial interests

The authors declare no competing financial interests.

References

- [1] K. Christopher, R. Dimitrios, A review on exergy comparison of hydrogen production methods from renewable energy sources, *Energy Environ. Sci.* 5 (2012) 6640-6651.
- [2] H. Xie, Z. Zhao, T. Liu, Y. Wu, C. Lan, W. Jiang, L. Zhu, Y. Wang, D. Yang, Z. Shao, A membrane-based seawater electrolyser for hydrogen generation, *Nature* 612 (2022) 673-678.
- [3] Z. Yu, L. Liu, Recent advances in hybrid seawater electrolysis for hydrogen production, *Adv. Mater.* 36 (2024) 2308647.
- [4] Z.Y. Yu, Y. Duan, X.Y. Feng, X. Yu, M.R. Gao, S.H. Yu, Clean and affordable hydrogen fuel from alkaline water splitting: past, recent progress, and future prospects, *Adv. Mater.* 33 (2021) 2007100.
- [5] W. Zhang, M. Liu, X. Gu, Y. Shi, Z. Deng, N. Cai, Water electrolysis toward elevated temperature: advances, challenges and frontiers, *Chem. Rev.* 123 (2023) 7119-7192.
- [6] J. Zhang, D. Chen, J. Jiao, W. Zeng, S. Mu, Valorization of spent lithium-ion battery cathode materials for energy conversion reactions, *Green Energy Environ.* (2024) <https://doi.org/10.1016/j.gee.2024.10.006>
- [7] Z. Pei, H. Zhang, D. Luan, X.W.D. Lou, Electrocatalytic acidic oxygen evolution:

- from catalyst design to industrial applications, *Matter* 6 (2023) 4128-4144.
- [8] J. Song, C. Wei, Z.-F. Huang, C. Liu, L. Zeng, X. Wang, Z.J. Xu, A review on fundamentals for designing oxygen evolution electrocatalysts, *Chem. Soc. Rev.* 49 (2020) 2196-2214.
- [9] X. Xie, L. Du, L. Yan, S. Park, Y. Qiu, J. Sokolowski, W. Wang, Y. Shao, Oxygen evolution reaction in alkaline environment: material challenges and solutions, *Adv. Funct. Mater.* 32 (2022) 2110036.
- [10] B. Zhang, X. Zheng, O. Voznyy, R. Comin, M. Bajdich, M. García-Melchor, L. Han, J. Xu, M. Liu, L. Zheng, F.P. García de Arquer, C.T. Dinh, F. Fan, M. Yuan, E. Yassitepe, N. Chen, T. Regier, P. Liu, Y. Li, P. De Luna, A. Janmohamed, H.L. Xin, H. Yang, A. Vojvodic, E.H. Sargent, Homogeneously dispersed multimetal oxygen-evolving catalysts, *Science* 352 (2016) 333-337.
- [11] S. Diyali, N. Diyali, B. Biswas, Coordination-driven electrocatalysts as an evolving wave of enthusiasm for sustainable hydrogen production, *Coord. Chem. Rev.* 500 (2024) 215496.
- [12] H. Hu, Z. Zhang, Y. Zhang, T. Thomas, H. Du, K. Huang, J.P. Attfield, M. Yang, An ultra-low Pt metal nitride electrocatalyst for sustainable seawater hydrogen production, *Energy Environ. Sci.* 16 (2023) 4584-4592.
- [13] I. Jang, K. Im, H. Shin, K.-S. Lee, H. Kim, J. Kim, S.J. Yoo, Electron-deficient titanium single-atom electrocatalyst for stable and efficient hydrogen production, *Nano Energy* 78 (2020) 105151.
- [14] Y. Jiao, Y. Zheng, K. Davey, S.-Z. Qiao, Activity origin and catalyst design principles for electrocatalytic hydrogen evolution on heteroatom-doped graphene, *Nat. Energy* 1 (2016) 16130.
- [15] Y. Liu, Y. Chen, Y. Tian, T. Sakthivel, H. Liu, S. Guo, H. Zeng, Z. Dai, Synergizing hydrogen spillover and deprotonation by the internal polarization field in a MoS₂/NiPS₃ vertical heterostructure for boosted water electrolysis, *Adv. Mater.* 34 (2022) 2203615.
- [16] X. Chen, L. Chen, C. Chen, D. Shi, J. Song, Y. Qin, X. Wang, M.M. Amjad, D. Sun, B. Sun, K. Zhang, Rational design of dynamic interface water evolution on tuning electrocatalyst toward the industrial hydrogen production, *Adv. Mater.* 36 (2024) 2401110.
- [17] Y. Song, C. Han, W. Li, X. Yi, Q. Liao, J. Zhou, Y. Zhou, Y. Ouyang, Y. Zhang, Q. Zheng, A. Pan, Engineering bimetallic cluster architectures: harnessing unique “remote synergy effect” between Mn and Y for enhanced electrocatalytic oxygen reduction reaction, *eScience* (2024) 100332.
- [18] X. Qiao, X. Yin, L. Wen, X. Chen, J. Li, H. Ye, X. Huang, W. Zhao, T. Wang, Variable nanosheets for highly efficient oxygen evolution reaction, *Chem* 8 (2022) 3241-3251.
- [19] P. Ji, D. Zheng, H. Jin, D. Chen, X. Luo, J. Yang, Z. Wang, S. Mu, Ultra-fast In situ reconstructed nickel (oxy) hydroxide nanoparticle crosslinked structure for super-efficient alkaline water electrolysis by sacrificing template strategy, *Small Struct.* 4 (2023) 2300013.
- [20] L. Lin, P. Su, Y. Han, Y. Xu, Q. Ni, X. Zhang, P. Xiong, Z. Sun, G. Sun, X. Chen,

Advances in regulating the electron spin effect toward electrocatalysis applications, *eScience* (2024) 100264.

- [21] J. Feng, X. Wang, H. Pan, In-situ reconstruction of catalyst in electrocatalysis, *Adv. Mater.* 36 2411688.
- [22] C. Chen, H. Jin, P. Wang, X. Sun, M. Jaroniec, Y. Zheng, S.-Z. Qiao, Local reaction environment in electrocatalysis, *Chem. Soc. Rev.* 53 (2024) 2022-2055.
- [23] F. Lin, M. Li, L. Zeng, M. Luo, S. Guo, Intermetallic nanocrystals for fuel-cells-based electrocatalysis, *Chem. Rev.* 123 (2023) 12507-12593.
- [24] M. Ning, S. Wang, J. Wan, Z. Xi, Q. Chen, H. Yu, Y. Sun, H. Li, T. Ma, H. Jin, Dynamic active sites in electrocatalysis, *Angew. Chem. Int. Ed.* 63 (2024) e202415794.
- [25] Q. Yao, Z. Yu, L. Li, X. Huang, Strain and surface engineering of multicomponent metallic nanomaterials with unconventional phases, *Chem. Rev.* 123 (2023) 9676-9717.
- [26] B. Jia, B. Zhang, Z. Cai, X. Yang, L. Li, L. Guo, Construction of amorphous/crystalline heterointerfaces for enhanced electrochemical processes, *eScience* 3 (2023) 100112.
- [27] A.A.H. Tajuddin, M. Wakisaka, T. Ohto, Y. Yu, H. Fukushima, H. Tanimoto, X. Li, Y. Misu, S. Jeong, J.-i. Fujita, H. Tada, T. Fujita, M. Takeguchi, K. Takano, K. Matsuoka, Y. Sato, Y. Ito, Corrosion-resistant and high-entropic non-noble-metal electrodes for oxygen evolution in acidic media, *Adv. Mater.* 35 (2023) 2207466.
- [28] X. Wang, J. Yang, M. Salla, S. Xi, Y. Yang, M. Li, F. Zhang, M.-K. Zhu, S. Huang, S. Huang, Y.-W. Zhang, Q. Wang, Redox-mediated ambient electrolytic nitrogen reduction for hydrazine and ammonia generation, *Angew. Chem. Int. Ed.* 60 (2021) 18721-18727.
- [29] H. Li, H. Huang, Y. Chen, F. Lai, H. Fu, L. Zhang, N. Zhang, S. Bai, T. Liu, High-entropy alloy aerogels: a new platform for carbon dioxide reduction, *Adv. Mater.* 35 (2023) 2209242.
- [30] G. Yang, J. Zhu, P. Yuan, Y. Hu, G. Qu, B.-A. Lu, X. Xue, H. Yin, W. Cheng, J. Cheng, W. Xu, J. Li, J. Hu, S. Mu, J.-N. Zhang, Regulating Fe-spin state by atomically dispersed Mn-N in Fe-N-C catalysts with high oxygen reduction activity, *Nat. Commun.* 12 (2021) 1734.
- [31] W. Ni, T. Wang, F. Héroguel, A. Krammer, S. Lee, L. Yao, A. Schüller, J.S. Luterbacher, Y. Yan, X. Hu, An efficient nickel hydrogen oxidation catalyst for hydroxide exchange membrane fuel cells, *Nat. Mater.* 21 (2022) 804-810.
- [32] Z.-S. Zhu, S. Zhong, C. Cheng, H. Zhou, H. Sun, X. Duan, S. Wang, Microenvironment engineering of heterogeneous catalysts for liquid-phase environmental catalysis, *Chem. Rev.* 124 (2024) 11348-11434.
- [33] J. Wang, J. Zhang, Y. Zhang, H. Li, P. Chen, C. You, M. Liu, H. Lin, S. Passerini, Atom-level tandem catalysis in lithium metal batteries, *Adv. Mater.* 36 (2024) 2402792.
- [34] X. Teng, D. Si, L. Chen, J. Shi, Synergetic catalytic effects by strong metal-support interaction for efficient electrocatalysis, *eScience* 4 (2024) 100272.
- [35] J. Li, W. Yin, J. Pan, Y. Zhang, F. Wang, L. Wang, Q. Zhao, External field assisted hydrogen evolution reaction, *Nano Res.* 16 (2023) 8638-8654.
- [36] Z. Feng, C. Dai, P. Shi, X. Lei, X. Liu, The role of photo in oxygen evolution reaction: A review, *Small* (2024) 2401578.

- [37] C. Hu, S. Tu, N. Tian, T. Ma, Y. Zhang, H. Huang, Photocatalysis enhanced by external fields, *Angew. Chem. Int. Ed.* 60 (2021) 16309-16328.
- [38] X. Li, C. Hao, Y. Du, Y. Lu, Y. Fan, M. Wang, N. Wang, R. Meng, X. Wang, Z.J. Xu, Harnessing magnetic fields to accelerate oxygen evolution reaction, *Chin. J. Catal.* 55 (2023) 191-199.
- [39] A.E. Thorarinsdottir, S.S. Veroneau, D.G. Nocera, Self-healing oxygen evolution catalysts, *Nat. Commun.* 13 (2022) 1243.
- [40] W. Yin, L. Yuan, H. Huang, Y. Cai, J. Pan, N. Sun, Q. Zhang, Q. Shu, C. Gu, Z. Zhuang, L. Wang, Strategies to accelerate bubble detachment for efficient hydrogen evolution, *Chin. Chem. Lett.* 35 (2024) 108351.
- [41] Q. Gao, S. Yang, C. Yuan, X. Liu, J. Zhao, G. Rao, C. Zhou, J. Xu, B. Zhu, W. Lei, The effect of multi-fields synergy from electric/light/thermal/force technologies on photovoltaic performance of Ba_{0.06}Bi_{0.47}Na_{0.47}TiO₃ ferroelectric ceramics via the Mg/Co substitution at A/B sites, *Small Methods* 8 (2024) 2301675.
- [42] B. Han, Z.C. Ma, Y.L. Zhang, L. Zhu, H. Fan, B. Bai, Q.D. Chen, G.Z. Yang, H.B. Sun, Reprogrammable soft robot actuation by synergistic magnetic and light fields, *Adv. Funct. Mater.* 32 (2022) 2110997.
- [43] L. Wu, Z. Li, Y. Song, Field synergy principle of heat and mass transfer, *Chin. Sci. Bull.* 54 (2009) 4604-4609.
- [44] B. Yang, K. Liu, H. Li, C. Liu, J. Fu, H. Li, J.E. Huang, P. Ou, T. Alkayyali, C. Cai, Accelerating CO₂ electroreduction to multicarbon products via synergistic electric-thermal field on copper nanoneedles, *J. Am. Chem. Soc.* 144 (2022) 3039-3049.
- [45] L. Fu, Y. Hu, X. Lin, Q. Wang, L. Yang, W. Xin, S. Zhou, Y. Qian, X.-Y. Kong, L. Jiang, L. Wen, Engineering multi-field-coupled synergistic ion transport system based on the heterogeneous nanofluidic membrane for high-efficient lithium extraction, *Nano-Micro Lett.* 15 (2023) 130.
- [46] D. Chen, R. Lu, R. Yu, Y. Dai, H. Zhao, D. Wu, P. Wang, J. Zhu, Z. Pu, L. Chen, S. Mu, Work-function-induced interfacial built-in electric fields in OS-OSSe₂ heterostructures for active acidic and alkaline hydrogen evolution, *Angew. Chem. Int. Ed.* 61 (2022) e202208642.
- [47] X. Mu, Y. Yuan, M. Yu, Y. Hu, W. Zeng, W. Peng, Y. Zhang, X. Liu, S. Liu, S. Mu, Robust water/seawater-electrolysis hydrogen production at industrial-scale current densities by modulating built-in-outer electric field of catalytic substance, *Nano Energy* (2024) 110216.
- [48] X. Mu, X. Zhang, Z. Chen, Y. Gao, M. Yu, D. Chen, H. Pan, S. Liu, D. Wang, S. Mu, Constructing symmetry-mismatched Ru_xFe_{3-x}O₄ heterointerface-supported Ru clusters for efficient hydrogen evolution and oxidation reactions, *Nano Lett.* 24 (2024) 1015-1023.
- [49] A. Grimaud, O. Diaz-Morales, B. Han, W.T. Hong, Y.-L. Lee, L. Giordano, K.A. Stoerzinger, M.T. Koper, Y. Shao-Horn, Activating lattice oxygen redox reactions in metal oxides to catalyse oxygen evolution, *Nat. Chem.* 9 (2017) 457-465.
- [50] J. Huang, C.N. Borca, T. Huthwelker, N.S. Yüzbaşı, D. Baster, M. El Kazzi, C.W. Schneider, T.J. Schmidt, E. Fabbri, Surface oxidation/spin state determines oxygen evolution reaction activity of cobalt-based catalysts in acidic environment, *Nat.*

Commun. 15 (2024) 3067.

[51] L. Li, P. Wang, Q. Shao, X. Huang, Recent progress in advanced electrocatalyst design for acidic oxygen evolution reaction, *Adv. Mater.* 33 (2021) 2004243.

[52] N.-T. Suen, S.-F. Hung, Q. Quan, N. Zhang, Y.-J. Xu, H.M. Chen, Electrocatalysis for the oxygen evolution reaction: recent development and future perspectives, *Chem. Soc. Rev.* 46 (2017) 337-365.

[53] Y. Zhao, H. Li, R. Yang, S. Xie, T. Liu, P. Li, Y. Liu, H. Li, F. Yang, T. Zhai, Transient phase transition during the hydrogen evolution reaction, *Energy Environ. Sci.* 16 (2023) 3951-3959.

[54] H. Zhu, S. Sun, J. Hao, Z. Zhuang, S. Zhang, T. Wang, Q. Kang, S. Lu, X. Wang, F. Lai, A high-entropy atomic environment converts inactive to active sites for electrocatalysis, *Energy Environ. Sci.* 16 (2023) 619-628.

[55] L. Wang, X. Zhou, Z. Luo, S. Liu, S. Yue, Y. Chen, Y. Liu, Review of external field effects on electrocatalysis: machine learning guided design, *Adv. Funct. Mater.* (2024) 2408870.

[56] S. Xue, Y. Gao, B. Wang, L. Zhi, Effects of external physical fields on electrocatalysis, *Chem Catal.* 3 (2023)

[57] W. Wang, T. Yu, Y. Cheng, X. Lei, B. Wang, R. Guo, X. Liu, J. You, X. Wang, H. Zhang, Field-assisted metal-air batteries: recent progress, mechanisms, and challenges, *Nano Energy* (2024) 109550.

[58] X. Li, W. Wang, F. Dong, Z. Zhang, L. Han, X. Luo, J. Huang, Z. Feng, Z. Chen, G. Jia, T. Zhang, Recent advances in noncontact external-field-assisted photocatalysis: from fundamentals to applications, *ACS Catal.* 11 (2021) 4739-4769.

[59] S. Tu, Y. Guo, Y. Zhang, C. Hu, T. Zhang, T. Ma, H. Huang, Piezocatalysis and piezo-photocatalysis: catalysts classification and modification strategy, reaction mechanism, and practical application, *Adv. Funct. Mater.* 30 (2020) 2005158.

[60] Z. Wang, Y. Li, C. Wu, S.C.E. Tsang, Electric-/magnetic-field-assisted photocatalysis: mechanisms and design strategies, *Joule* 6 (2022) 1798-1825.

[61] Y. Xu, R. Zhao, S. Li, Z. Lv, J. He, J. Song, Mass transfer and energy conversion in electrochemical process assisted by external fields, *Energy Convers. Manage.* 321 (2024) 119069.

[62] K. Wei, X. Wang, J. Ge, Towards bridging thermo/electrocatalytic CO oxidation: from nanoparticles to single atoms, *Chem. Soc. Rev.* 53 (2024) 8903-8948.

[63] Z. Feng, C. Dai, H. Wang, R. Guo, J. You, X. Liu, Recent development of external magnetic field assisted oxygen evolution reaction-a mini review, *ChemCatChem* 15 (2023) e202300688.

[64] H. Liu, W. Cai, Recent progress in electric-field assisted combustion: a brief review, *Front. Energy* (2022) 1-17.

[65] B. Dai, J. Guo, C. Gao, H. Yin, Y. Xie, Z. Lin, Recent advances in efficient photocatalysis via modulation of electric and magnetic fields and reactive phase control, *Adv. Mater.* 35 (2023) 2210914.

[66] W. Lai, Y. Qiao, J. Zhang, Z. Lin, H. Huang, Design strategies for markedly enhancing energy efficiency in the electrocatalytic CO₂ reduction reaction, *Energy Environ. Sci.* 15 (2022) 3603-3629.

- [67] X. Yang, Y. Wang, X. Tong, N. Yang, Strain engineering in electrocatalysts: fundamentals, progress, and perspectives, *Adv. Energy Mater.* 12 (2022) 2102261.
- [68] C.Y. Zhang, C. Zhang, J.L. Pan, G.W. Sun, Z. Shi, C. Li, X. Chang, G.Z. Sun, J.Y. Zhou, A. Cabot, Surface strain-enhanced MoS₂ as a high-performance cathode catalyst for lithium–sulfur batteries, *eScience* 2 (2022) 405-415.
- [69] J. Yao, W. Huang, W. Fang, M. Kuang, N. Jia, H. Ren, D. Liu, C. Lv, C. Liu, J. Xu, Q. Yan, Promoting electrocatalytic hydrogen evolution reaction and oxygen evolution reaction by fields: effects of electric field, magnetic field, strain, and light, *Small Methods* 4 (2020) 2000494.
- [70] Y. Guo, W. Shi, Y. Zhu, Internal electric field engineering for steering photogenerated charge separation and enhancing photoactivity, *EcoMat* 1 (2019) e12007.
- [71] K. Mitra, A. Adalder, S. Mandal, U.K. Ghorai, Enhancing electrochemical reactivity with magnetic fields: unraveling the role of magneto-electrochemistry, *Small Methods* (2024) 2301132.
- [72] S. Luo, K. Elouarzaki, Z.J. Xu, Electrochemistry in magnetic fields, *Angew. Chem. Int. Ed.* 61 (2022) e202203564.
- [73] Y. Zhang, M. Shahriar, S. Hu, Structuring electrodes via acoustic-field-assisted particle patterning for enhanced performance of lithium-ion batteries, *J. Mater. Chem. A* 11 (2023) 11849-11858.
- [74] H. Zhang, F. Song, Recent advances in photo-assisted electrocatalysts for energy conversion, *J. Mater. Chem. A* 9 (2021) 27193-27214.
- [75] Y. Liu, Y. Shi, C. Gao, Z. Shi, H. Ding, Y. Feng, Y. He, J. Sha, J. Zhou, B. Lu, Low-temperature potassium batteries enabled by electric and thermal field regulation, *Angew. Chem.* 135 (2023) e202300016.
- [76] F. Xie, Y. Du, M. Lu, S. Yan, Z. Zou, Thermal-stimulated spin disordering accelerates water electrolysis, *Energy Environ. Sci.* 18 (2025) 1972-1983.
- [77] M. Lu, Y. Du, S. Yan, T. Yu, Z. Zou, Thermal suppression of charge disproportionation accelerates interface electron transfer of water electrolysis, *Proc. Natl. Acad. Sci. U S A* 121 (2024) e2316054120.
- [78] H. Zhong, X. Wang, G. Sun, Y. Tang, S. Tan, Q. He, J. Zhang, T. Xiong, C. Diao, Z. Yu, S. Xi, W.S.V. Lee, J. Xue, Optimization of oxygen evolution activity by tuning e*_g band broadening in nickel oxyhydroxide, *Energy Environ. Sci.* 16 (2023) 641-652.
- [79] W. Cheng, X. Zhao, H. Su, F. Tang, W. Che, H. Zhang, Q. Liu, Lattice-strained metal–organic-framework arrays for bifunctional oxygen electrocatalysis, *Nat. Energy* 4 (2019) 115-122.
- [80] T. Tang, X. Liu, X. Luo, Z. Xue, H.-R. Pan, J. Fu, Z.-C. Yao, Z. Jiang, Z.-H. Lyu, L. Zheng, D. Su, J.-N. Zhang, L. Zhang, J.-S. Hu, Unconventional bilateral compressive strained ni–ir interface synergistically accelerates alkaline hydrogen oxidation, *J. Am. Chem. Soc.* 145 (2023) 13805-13815.
- [81] Ö. Akay, J. Poon, C. Robertson, F.F. Abdi, B.R. Cuenya, M. Giersig, K. Brinkert, Releasing the bubbles: nanotopographical electrocatalyst design for efficient photoelectrochemical hydrogen production in microgravity environment, *Adv. Sci.* 9 (2022) 2105380.

- [82] K. Yan, T.A. Maark, A. Khorshidi, V.A. Sethuraman, A.A. Peterson, P.R. Guduru, The influence of elastic strain on catalytic activity in the hydrogen evolution reaction, *Angew. Chem. Int. Ed.* 55 (2016) 6175-6181.
- [83] J. Huang, Z. Zhuang, Y. Zhao, J. Chen, Z. Zhuo, Y. Liu, N. Lu, H. Li, T. Zhai, Back-Gated van der Waals Heterojunction Manipulates Local Charges toward Fine-Tuning Hydrogen Evolution, *Angew. Chem. Int. Ed.* 61 (2022) e202203522.
- [84] J. Li, J. Li, J. Ren, H. Hong, D. Liu, L. Liu, D. Wang, Electric-field-treated Ni/Co₃O₄ film as high-performance bifunctional electrocatalysts for efficient overall water splitting, *Nano-Micro Lett.* 14 (2022) 148.
- [85] D. Zheng, K. Liu, Z. Zhang, Q. Fu, M. Bian, X. Han, X. Shen, X. Chen, H. Xie, X. Wang, X. Yang, Y. Zhang, S. Song, Essential features of weak current for excellent enhancement of NO_x reduction over monoatomic V-based catalyst, *Nat. Commun.* 15 (2024) 6688.
- [86] J. Wang, M. Yan, K. Zhao, X. Liao, P. Wang, X. Pan, W. Yang, L. Mai, Field effect enhanced hydrogen evolution reaction of MoS₂ nanosheets, *Adv. Mater* 29 (2017) 1604464.
- [87] X. Pan, M. Yan, Q. Liu, X. Zhou, X. Liao, C. Sun, J. Zhu, C. McAleese, P. Couture, M.K. Sharpe, R. Smith, N. Peng, J. England, S.C.E. Tsang, Y. Zhao, L. Mai, Electric-field-assisted proton coupling enhanced oxygen evolution reaction, *Nat. Commun.* 15 (2024) 3354.
- [88] Y. Pan, X. Wang, W. Zhang, L. Tang, Z. Mu, C. Liu, B. Tian, M. Fei, Y. Sun, H. Su, L. Gao, P. Wang, X. Duan, J. Ma, M. Ding, Boosting the performance of single-atom catalysts via external electric field polarization, *Nat. Commun.* 13 (2022) 3063.
- [89] M. Yan, X. Pan, P. Wang, F. Chen, L. He, G. Jiang, J. Wang, J.Z. Liu, X. Xu, X. Liao, J. Yang, L. Mai, Field-effect tuned adsorption dynamics of VSe₂ nanosheets for enhanced hydrogen evolution reaction, *Nano Lett.* 17 (2017) 4109-4115.
- [90] T. Xu, F. Tian, D. Jiao, J. Fan, Z. Jin, L. Zhang, W. Zhang, L. Zheng, D.J. Singh, L. Zhang, W. Zheng, X. Cui, In situ construction of built-in opposite electric field balanced surface adsorption for hydrogen evolution reaction, *Small* 20 (2024) 2309249.
- [91] D. Chen, R. Lu, R. Yu, Y. Dai, H. Zhao, D. Wu, P. Wang, J. Zhu, Z. Pu, L. Chen, J. Yu, S. Mu, Work-function-induced interfacial built-in electric fields in Os-OsSe₂ heterostructures for active acidic and alkaline hydrogen evolution, *Angew. Chem. Int. Ed.* 61 (2022) e202208642.
- [92] X. Ren, T. Wu, Y. Sun, Y. Li, G. Xian, X. Liu, C. Shen, J. Gracia, H.-J. Gao, H. Yang, Z.J. Xu, Spin-polarized oxygen evolution reaction under magnetic field, *Nat. Commun.* 12 (2021) 2608.
- [93] T. Sun, Z. Tang, W. Zang, Z. Li, J. Li, Z. Li, L. Cao, J.S. Dominic Rodriguez, C.O.M. Mariano, H. Xu, Ferromagnetic single-atom spin catalyst for boosting water splitting, *Nat. Nanotechnology* 18 (2023) 763-771.
- [94] Y. Zhang, P. Guo, S. Niu, J. Wu, W. Wang, B. Song, X. Wang, Z. Jiang, P. Xu, Magnetic field enhanced electrocatalytic oxygen evolution of NiFe-LDH/Co₃O₄ p-n heterojunction supported on nickel foam, *Small methods* 6 (2022) 2200084.
- [95] Y. Zhang, P. Guo, S. Li, J. Sun, W. Wang, B. Song, X. Yang, X. Wang, Z. Jiang, G. Wu, P. Xu, Magnetic field assisted electrocatalytic oxygen evolution reaction of nickel-

- based materials, *J. Mater. Chem. A* 10 (2022) 1760-1767.
- [96] X. Ren, T. Wu, Z. Gong, L. Pan, J. Meng, H. Yang, F.B. Dagbjartsdottir, A. Fisher, H.-J. Gao, Z.J. Xu, The origin of magnetization-caused increment in water oxidation, *Nat. Commun.* 14 (2023) 2482.
- [97] J. Yan, Y. Wang, Y. Zhang, S. Xia, J. Yu, B. Ding, Direct magnetic reinforcement of electrocatalytic ORR/OER with electromagnetic induction of magnetic catalysts, *Adv. Mater.* 33 (2021) 2007525.
- [98] Z. Zhu, W. Tang, J. Wang, Y. Lin, Z. Li, H. Chen, X. Niu, J.S. Chen, R. Wu, Regulating the magnetic domain of nickel for enhanced CO₂ electrochemical reduction driven by external magnetic field, *Adv. Energy Mater.* 15 (2025) 2403624.
- [99] Z. Zhang, L. Jia, T. Li, J. Qian, X. Liang, D. Xue, D. Gao, In-situ magnetic field enhanced performances in ferromagnetic FeCo₂O₄ nanofibers-based rechargeable Zinc–air batteries, *J. Energy Chem.* 78 (2023) 447-453.
- [100] L. Lin, Y. Xu, Y. Han, R. Xu, T. Wang, Z. Sun, Z. Yan, Spin-magnetic effect of d- π conjugation polymer enhanced O–H cleavage in water oxidation, *J. Am. Chem. Soc.* 146 (2024) 7363-7372.
- [101] T. Wu, X. Ren, Y. Sun, S. Sun, G. Xian, G.G. Scherer, A.C. Fisher, D. Mandler, J.W. Ager, A. Grimaud, J. Wang, C. Shen, H. Yang, J. Gracia, H.-J. Gao, Z.J. Xu, Spin pinning effect to reconstructed oxyhydroxide layer on ferromagnetic oxides for enhanced water oxidation, *Nat. Commun.* 12 (2021) 3634.
- [102] X. Zhang, H. Zhong, Q. Zhang, Q. Zhang, C. Wu, J. Yu, Y. Ma, H. An, H. Wang, Y. Zou, C. Diao, J. Chen, Z.G. Yu, S. Xi, X. Wang, J. Xue, High-spin Co³⁺ in cobalt oxyhydroxide for efficient water oxidation, *Nat. Commun.* 15 (2024) 1383.
- [103] G. Zhou, P. Wang, H. Li, B. Hu, Y. Sun, R. Huang, L. Liu, Spin-state reconfiguration induced by alternating magnetic field for efficient oxygen evolution reaction, *Nat. Commun.* 12 (2021) 4827.
- [104] J. Dulle, S. Nemeth, E.V. Skorb, T. Irrgang, J. Senker, R. Kempe, A. Fery, D.V. Andreeva, Sonochemical activation of Al/Ni hydrogenation catalyst, *Adv. Funct. Mater.* 22 (2012) 3128-3135.
- [105] Y. Ehrnst, P.C. Sherrell, A.R. Rezk, L.Y. Yeo, Acoustically-induced water frustration for enhanced hydrogen evolution reaction in neutral electrolytes, *Adv. Energy Mater.* 13 (2023) 2203164.
- [106] F. Foroughi, A.Y. Faid, S. Sunde, B.G. Pollet, Sonoactivated polycrystalline Ni electrodes for alkaline oxygen evolution reaction, *Ultrason. Sonochem.* 86 (2022) 106013.
- [107] S. Guo, J. Su, H. Luo, X. Duan, Q. Shen, J. Xue, B. Wei, X.-M. Zhang, Boosting photocatalytic hydrogen evolution reaction by the improved mass flow and energy flow process based on ultrasound waves, *ACS Catal.* 13 (2022) 296-307.
- [108] J. Zhang, Z. Zhou, Y. Wang, Q. Chen, G. Hou, Y. Tang, Ultrasonic-assisted enhancement of lithium-oxygen battery, *Nano Energy* 102 (2022) 107655.
- [109] G. Righi, J. Plescher, F.-P. Schmidt, R.K. Campen, S. Fabris, A. Knop-Gericke, R. Schlögl, T.E. Jones, D. Teschner, S. Piccinin, On the origin of multihole oxygen evolution in hematite photoanodes, *Nat. Catal.* 5 (2022) 888-899.
- [110] Q.-J. Wu, D.-H. Si, S. Ye, Y.-L. Dong, R. Cao, Y.-B. Huang, Photocoupled

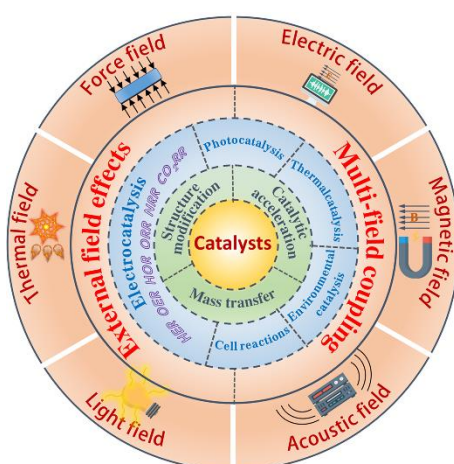
- electroreduction of CO₂ over photosensitizer-decorated covalent organic frameworks, *J. Am. Chem. Soc.* 145 (2023) 19856-19865.
- [111] X. Wang, S. Xi, P. Huang, Y. Du, H. Zhong, Q. Wang, A. Borgna, Y.-W. Zhang, Z. Wang, H. Wang, Z.G. Yu, W.S.V. Lee, J. Xue, Pivotal role of reversible NiO₆ geometric conversion in oxygen evolution, *Nature* 611 (2022) 702-708.
- [112] H. Zhong, Q. Zhang, J. Yu, X. Zhang, C. Wu, H. An, Y. Ma, H. Wang, J. Zhang, Y.-W. Zhang, C. Diao, Z.G. Yu, S. Xi, X. Wang, J. Xue, Key role of eg* band broadening in nickel-based oxyhydroxides on coupled oxygen evolution mechanism, *Nat. Commun.* 14 (2023) 7488.
- [113] W. Liang, M. Xie, D. Li, W. Qin, C. Dai, Y. Wang, H. Zhang, B. Zhao, G. Jin, Y. Sun, L. Jiang, Plasmon-promoted interatomic hot carriers regulation enhanced electrocatalytic nitrogen reduction reaction, *Angew. Chem. Int. Ed.* 63 (2024) e202409484.
- [114] X. Wu, J. Wang, Z. Wang, F. Sun, Y. Liu, K. Wu, X. Meng, J. Qiu, Boosting the electrocatalysis of mxenes by plasmon-induced thermalization and hot-electron injection, *Angew. Chem. Int. Ed.* 60 (2021) 9416-9420.
- [115] B. Deng, G. Yu, W. Zhao, Y. Long, C. Yang, P. Du, X. He, Z. Zhang, K. Huang, X. Li, H. Wu, A self-circulating pathway for the oxygen evolution reaction, *Energy Environ. Sci.* 16 (2023) 5210-5219.
- [116] Y. Wu, G. Huang, S. Du, M. Li, Q. Liu, Y. Zhou, Z. Jiang, X. Zhu, Y. Wang, T. Wang, L. Tao, S. Wang, Electrocatalysis boosts the methanol thermocatalytic dehydrogenation for high-purity H₂ and CO production, *J. Am. Chem. Soc.* 146 (2024) 9657-9664.
- [117] Y. Du, F. Xie, M. Lu, R. Lv, W. Liu, Y. Yan, S. Yan, Z. Zou, Continuous strain tuning of oxygen evolution catalysts with anisotropic thermal expansion, *Nat. Commun.* 15 (2024) 1780.
- [118] X. Fan, S. Tan, J. Yang, Y. Liu, W. Bian, F. Liao, H. Lin, Y. Li, From theory to experiment: Cascading of thermocatalysis and electrolysis in oxygen evolution reactions, *ACS Energy Lett.* 7 (2021) 343-348.
- [119] K. Liu, H. Li, M. Xie, P. Wang, Z. Jin, Y. Liu, M. Zhou, P. Li, G. Yu, Thermally enhanced relay electrocatalysis of nitrate-to-ammonia reduction over single-atom-alloy oxides, *J. Am. Chem. Soc.* 146 (2024) 7779-7790.
- [120] Y. Ma, Y. Zhou, C. Wang, B. Gao, J. Li, M. Zhu, H. Wu, C. Zhang, Y. Qin, Photothermal-magnetic synergistic effects in an electrocatalyst for efficient water splitting under optical-magnetic fields, *Adv. Mater.* 35 (2023) 2303741.
- [121] S.-L. Tian, L.-N. Song, L.-M. Chang, W.-Q. Liu, H.-F. Wang, J.-J. Xu, A magnetic/force coupling assisted lithium-oxygen battery based on magnetostriction and piezoelectric catalysis of CoFe₂O₄/BiFeO₃ cathode, *Nano Energy* 126 (2024) 109677.
- [122] M. Lu, G. Li, S. Yan, L. Zhang, T. Yu, Z. Zou, Heat-induced magnetic transition for water electrolysis on NiFeN@NiFeOOH core-shell assembly, *Nano Lett.* 22 (2022) 9131-9137.
- [123] T. Li, Y. Zou, Z. Liu, Magnetic-thermal external field activate the pyro-magnetic effect of pyroelectric crystal (NaNbO₃) to build a promising multi-field coupling-assisted photoelectrochemical water splitting system, *Appl. Catal., B-Environ.* 328

(2023) 122486.

- [124] D. Liu, M. Lu, D. Liu, S. Yan, W. Zhou, L. Zhang, Z. Zou, Heat-triggered ferri-to-paramagnetic transition accelerates redox couple-mediated electrocatalytic water oxidation, *Adv. Funct. Mater.* 32 (2022) 2111234.
- [125] L. Gao, X. Cui, Z. Wang, C.D. Sewell, Z. Li, S. Liang, M. Zhang, J. Li, Y. Hu, Z. Lin, Operando unraveling photothermal-promoted dynamic active-sites generation in NiFe₂O₄ for markedly enhanced oxygen evolution, *Proc. Natl. Acad. Sci. U S A* 118 (2021) e2023421118.
- [126] Z. Cai, L. Li, P. Ding, D. Pang, M. Xu, Z. Xu, J. Kang, T. Guo, G. Teobaldi, Z. Wang, L.-M. Liu, L. Guo, High-valence Cu induced by photoelectric reconstruction for dynamically stable oxygen evolution sites, *J. Am. Chem. Soc.* 146 (2024) 19295-19302.
- [127] M. Jiang, J. Xu, Y. Chen, L. Wang, P. Munroe, Z.-H. Xie, S. Peng, High-efficiency photo-assisted large current-density water splitting with mott-schottky heterojunctions, *Angew. Chem. Int. Ed.* 64 (2025) e202415492.
- [128] Y. Zhang, L. Hu, Y. Zhang, X. Wang, H. Wang, Snowflake-Like Cu₂S/MoS₂/Pt heterostructure with near infrared photothermal-enhanced electrocatalytic and photoelectrocatalytic hydrogen production, *Appl. Catal., B-Environ.* 315 (2022) 121540.
- [129] Z. Tu, C. Mu, Y. Yao, L. Wu, Y. Zou, Z. Tong, K. Huang, Recent advances in unconventional heating and external field-assisted enhancement for dry reforming of methane, *Chem. Eng. J.* (2024) 148899.
- [130] H.C. Prakash, M.S. Kumar, T.-W. Lin, S.K. Batabyal, Photo-assisted capacitive performance of V₂O₅ supercapacitor, *Electrochim. Acta* 469 (2023) 143229.
- [131] J. Song, M. Yan, J. Ye, S. Zheng, L.Y. Ee, Z. Wang, J. Li, M. Huang, Research progress in external field intensification of forward osmosis process for water treatment: a critical review, *Water Res.* 222 (2022) 118943.
- [132] H. Li, Y. Li, L. Zhang, Z. Chen, X. Sun, Field-assisted electrocatalysts spark sulfur redox kinetics: from fundamentals to applications, *Interdi. Mater.* 2 (2023) 390-415.
- [133] C.Y. Zhang, C. Zhang, G.W. Sun, J.L. Pan, L. Gong, G.Z. Sun, J.J. Biendicho, L. Balcells, X.L. Fan, J.R. Morante, J.Y. Zhou, A. Cabot, Spin effect to promote reaction kinetics and overall performance of lithium-sulfur batteries under external magnetic field, *Angew. Chem. Int. Ed.* 61 (2022) e202211570.
- [134] C. Tan, R. Li, J. Su, D. Du, Y. Du, B. Attard, Y. Chew, H. Zhang, E.J. Lavernia, Y. Fautrelle, J. Teng, A. Dong, Review on field assisted metal additive manufacturing, *Int. J. Mach. Tool. Manu.* 189 (2023) 104032.
- [135] R. Li, L.-P. Qiu, S.-Z. Cao, Z. Li, S.-L. Gao, J. Zhang, S. Ramakrishna, Y.-Z. Long, Research advances in magnetic field-assisted photocatalysis, *Adv. Funct. Mater.* 34 (2024) 2316725.
- [136] W. Liu, P. Wang, Y. Ao, J. Chen, X. Gao, B. Jia, T. Ma, Directing charge transfer in a chemical-bonded BaTiO₃@ReS₂ schottky heterojunction for piezoelectric enhanced photocatalysis, *Adv. Mater.* 34 (2022) 2202508.
- [137] W. Gao, J. Lu, S. Zhang, X. Zhang, Z. Wang, W. Qin, J. Wang, W. Zhou, H. Liu, Y. Sang, Suppressing photoinduced charge recombination via the lorentz force in a

- photocatalytic system, *Adv. Sci.* 6 (2019) 1901244.
- [138] B. He, S. Jia, M. Zhao, Y. Wang, T. Chen, S. Zhao, Z. Li, Z. Lin, Y. Zhao, X. Liu, General and robust photothermal-heating-enabled high-efficiency photoelectrochemical water splitting, *Adv. Mater.* 33 (2021) 2004406.
- [139] B. Dai, C. Gao, J. Guo, M. Ding, Q. Xu, S. He, Y. Mou, H. Dong, M. Hu, Z. Dai, Y. Zhang, Y. Xie, Z. Lin, A robust pyro-phototronic route to markedly enhanced photocatalytic disinfection, *Nano Lett.* 24 (2024) 4816-4825.
- [140] B.S. Zhang, Y. Wang, N. Zhang, J. Zhu, W. Ji, F. Chen, X. Chen, Y. Yu, B. Zhang, Electromagnetic field-assisted low-temperature ammonia synthesis, *Sci. Bull.* 68 (2023) 1871-1874.
- [141] C. Guo, Y. Tang, Z. Yang, T. Zhao, J. Liu, Y. Zhao, F. Wang, Reinforcing the efficiency of photothermal catalytic CO₂ methanation through integration of Ru nanoparticles with photothermal MnCo₂O₄ nanosheets, *ACS Nano* 17 (2023) 23761-23771.
- [142] X. Wang, L. Chen, Y. Yu, W. Wang, L. Yue, Z. Shao, H. Wu, Y. Li, Tuning p-band centers and interfacial built-in electric field of heterostructure catalysts to expedite bidirectional sulfur redox for high-performance Li-S batteries, *Adv. Funct. Mater.* 34 (2024) 2406290.
- [143] Z. Gao, Y. Schwab, Y. Zhang, N. Song, X. Li, Ferromagnetic nanoparticle-assisted polysulfide trapping for enhanced Lithium-Sulfur batteries, *Adv. Funct. Mater.* 28 (2018) 1800563.
- [144] L. Bai, H. Huang, S. Zhang, L. Hao, Z. Zhang, H. Li, L. Sun, L. Guo, H. Huang, Y. Zhang, Photocatalysis-assisted Co₃O₄/g-C₃N₄ p-n junction all-solid-state supercapacitors: a bridge between energy storage and photocatalysis, *Adv. Sci.* 7 (2020) 2001939.
- [145] Y. Lin, L. Feng, X. Li, Y. Chen, G. Yin, W. Zhou, Study on ultrasound-assisted oxidative desulfurization for crude oil, *Ultrason. Sonochem.* 63 (2020) 104946.
- [146] M. Li, J. Zhang, S. Liang, M. Li, H. Wu, Novel magnetic coupling constructed wetland for nitrogen removal: enhancing performance and responses of plants and microbial communities, *Sci. Total Environ.* 819 (2022) 152040.
- [147] W. Li, G. Liao, W. Duan, F. Gao, Y. Wang, R. Cui, X. Wang, C. Wang, Synergistically electronic interacted PVDF/CdS/TiO₂ organic-inorganic photocatalytic membrane for multi-field driven panel wastewater purification, *Appl. Catal. B-Environ. Energy* 354 (2024) 124108.
- [148] F. Mushtaq, X. Chen, H. Torlakcik, C. Steuer, M. Hoop, E.C. Siringil, X. Marti, G. Limburg, P. Stipp, B.J. Nelson, S. Pané, Magnetoelectrically driven catalytic degradation of organics, *Adv. Mater.* 31 (2019) 1901378.
- [149] Z.-Y. Huo, Y.-J. Kim, I.-Y. Suh, D.-M. Lee, J.H. Lee, Y. Du, S. Wang, H.-J. Yoon, S.-W. Kim, Triboelectrification induced self-powered microbial disinfection using nanowire-enhanced localized electric field, *Nat. Commun.* 12 (2021) 3693.

Graphical Abstract



This review investigates the effect of external fields on catalysis for energy–environment systems and the catalytic mechanisms involved, including mass transfer, structural modification, and accelerated reaction kinetics, which profoundly influence the application of catalysts and the development of in situ field-enhanced catalysis.

Highlights

- The latest developments in external field-assisted methods for enhancing the performance of catalysts are systematically summarized.
- External field effects, related catalysis mechanisms, and external field-enhanced catalysis are highlighted.
- The major challenges for external field-assisted catalysis are analyzed, and countermeasures are proposed.
- The significance and opportunities for external field-assisted catalysis and beyond are pointed out.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: