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Investigating the role of oxygen vacancies in metal oxide for enhanced electrochemical reduction of NO_3^- to NH_3 : mechanistic insights

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Ammonia (NH_3) is a crucial chemical commodity used extensively in fertilizer production and as a renewable potential energy carrier. Conventionally, NH_3 synthesis relies on the energy-intensive Haber–Bosch process, which requires elevated temperatures and pressures. However, the demanding conditions of this method have led to research into electrochemical NH_3 synthesis via nitrate (NO_3^-) and water, creating a sustainable environment. The electrochemical nitrate reduction reaction (NO_3RR) emerged as a promising eco-friendly alternative, boasting reduced energy consumption and mild reaction conditions. Moreover, the NO_3RR is capable of achieving a high NH_3 yield and faradaic efficiency (FE) but poses challenges due to the competing hydrogen evolution reaction (HER), etc. To address these issues, it is essential to tailor the structure of the electrocatalysts, such as incorporating oxygen vacancies (OVs) and controlling the coordination environment and local electronegativity. This review offers a thorough description of current developments in the identification, processing, and use of OVs for the NO_3RR . We highlight different OV generation processes and the associated assessment methodologies. Lastly, we discuss the challenges and opportunities of designing metal oxide catalysts with OVs for NO_3RR , aiming to accelerate the development of exceptional electrocatalysts and contribute to a sustainable future for ammonia generation.

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1. Introduction

Ammonia (NH_3) is one of the most widely produced synthetic chemicals globally, primarily used in fertilizer manufacturing and the production of fibers, plastics, explosives, and other fine chemicals.^{1,2} Recently, it has gained significant interest as a portable energy carrier due to its high energy density and zero carbon emissions, making it a valuable resource.^{3,4} The primary method for industrial NH_3 production is the Haber–Bosch process, which involves harsh operating conditions,

including temperatures of 400–600 °C and pressures ranging from 150–350 atm. These conditions result in substantial energy consumption, accounting for approximately 1–2% of global energy usage and significant carbon emissions.^{5,6} Consequently, scientists are actively seeking alternative and efficient methods for NH_3 synthesis to replace the conventional approach. Among the various options available, the NO_3RR route presents an optimal solution regarding economic feasibility and environmental sustainability.^{7,8} Recently, considerable research efforts have been dedicated to investigating diverse innovative methods for electrochemically reducing N_2 to produce NH_3 .^{9–13} However, the process continues to face challenges in terms of low yield rates and faradaic efficiency (FE),^{3,14–16} falling short of the industrial standard for NH_3 production.^{17,18} These obstacles arise due to the exceptionally high decomposition energy of the triple bond in N_2 (941 kJ mol⁻¹) and the limited solubility of N_2 in water.^{19–22} Furthermore, the dissociation of the first bond in $\text{N}\equiv\text{N}$ necessitates an energy input of 410 kJ mol⁻¹, rendering the activation of N_2 exceptionally challenging and energetically demanding. Similarly, the electrochemical conversion of N_2 to NH_3 faces substantial impediments due to the intense competition posed by the side product, namely the hydrogen evolution reaction (HER), observed across traditional catalysts, such as Rh, Fe, and Ru.^{23,24} This is attributed to the fact that its theoretical reaction potential

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(0.09 V vs. RHE) closely resembles that of the hydrogen evolution reaction (HER).

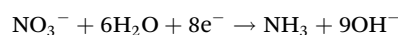
While nitric oxide (NO) is a more reactive nitrogen source compared with N₂, its limited solubility in aqueous electrolytes poses a significant obstacle for NO electroreduction. This requirement for concentrated NO hampers its progress and impedes further development. Many noble metals exhibit promising NORR activity, with NH₃ being the main reduction product with numerous catalysts.^{8,25,26} However, their scarcity imposes severe limitations on their widespread utilization. Consequently, the pursuit of cost-effective materials for electrochemical NORR catalysis remains a formidable challenge. Though Cu foam demonstrated an impressive NH₃ faradaic efficiency (FE) of 93.5% when utilizing NO from exhaust emissions, it is important to note that the direct use of concentrated NO gas, as described in the study, could present a significant hurdle to its commercial viability. This is due to the necessity for an additional facility for the concentration of NO gas extracted from exhaust emissions. In a similar way, Kim *et al.*²⁷ accomplished the precise electroreduction of NO to NH₃ with nearly 100% NH₃ FE using a nanostructured silver electrode and an electrolyte devised by EFeMC (EDTA-Fe²⁺ metal complex), with the initial NO concentration set at 1%. Nonetheless, when assessing the economic viability of this setup, the researchers determined that the cost of producing NH₃ through the NORR in the EFeMC-designed electrolyte was roughly 2.5 times greater than the prevailing commercial NH₃ price. In practice, NO concentrations in real-world exhaust gases tend to be relatively low, whereas previous research on electrochemical NORR has predominantly centered around high-concentration NO. Therefore, future investigations should delve into advanced NORR electrocatalysts capable of performing effectively with low-concentration NO or even real exhaust gases. To sum it up, the limited availability of effective

and selective catalysts, the complexities related to NO solubility in aqueous solutions, and the necessity for an additional step to concentrate NO collectively impede further advancements in the electrochemical production of NH₃ from NO.

In contrast, the electrochemical reduction of nitrate offers a promising alternative as it does not require the breaking of high-energy bonds (204 kJ mol⁻¹), allowing for faster reaction rates and enhanced NH₃ production; see Table 2.^{18,28} Moreover, the substantial difference in the standard reduction potential between nitrate (NO₃⁻; 0.69 V vs. RHE) reduction and the HER implies that NO₃⁻ reduction effectively avoids the hindrance caused by competing for the HER (Fig. 1a).²⁹ Furthermore, NO₃⁻ serves as an abundant nitrogen source, particularly in industrial wastewater and contaminated groundwater, contributing to the worldwide nitrogen cycle imbalance.³⁰ Consequently, a viable approach to “turn waste into wealth” and establish a closed N-cycle (Fig. 1b, pathway 1) involves utilizing renewable energy sources to drive electrochemical NO₃⁻-to-NH₃ conversion, thereby mitigating the adverse effects of nitrates on public health.^{31,32}

Recently, there has been an interest in the electrocatalytic NO₃RR to yield valuable NH₃.^{34–36} This methodology utilizes water as the primary source and can be sustained by renewable energy sources such as wind and solar energy. Yet, its efficacy is undermined by the occurrence of side reactions, including the HER.³⁷ Therefore, there is an urgent need for high-performance electrocatalysts with outstanding selectivity and stability. The electrode materials significantly influence the reaction kinetics and product selectivity in the electrochemical NO₃RR.

The typical half-cell reaction for the NO₃RR is as follows:



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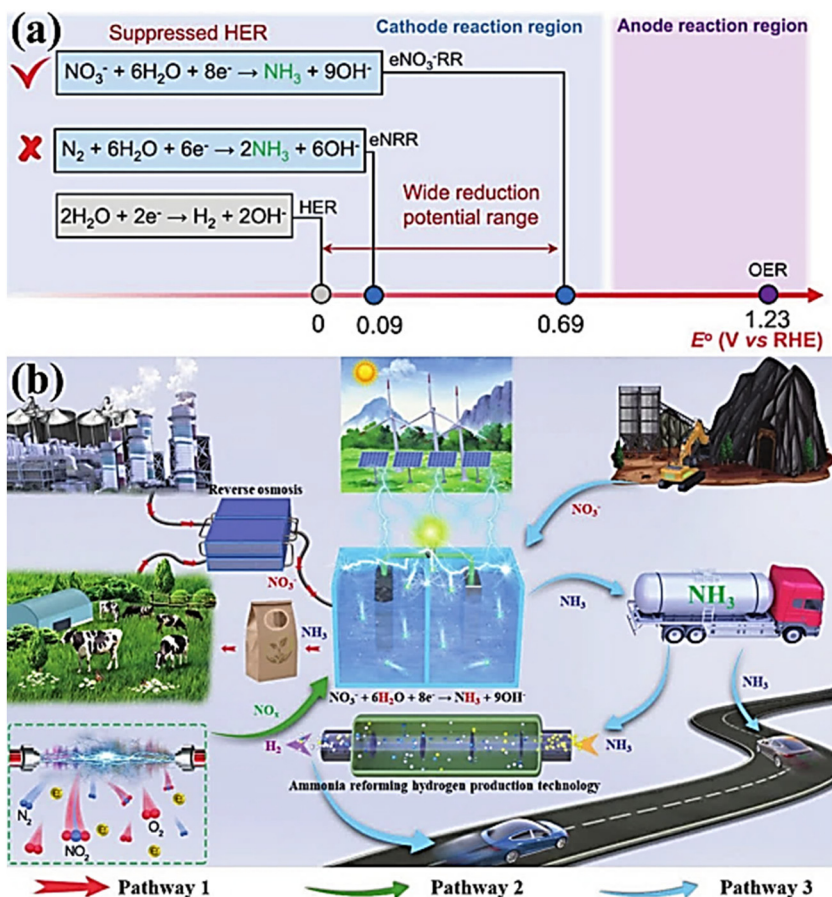


Fig. 1 (a) The standard reduction potentials for the HER, NRR, and NO₃RR were compared. Reproduced from ref. 29 with permission from the American Chemical Society, copyright 2022. (b) The design schematic illustration of the NO₃RR process to NH₃. Reproduced from ref. 33 with permission from Wiley, copyright 2023.

In this context, the main goal of catalysts is to guide the reduction process toward the production of ammonia while simultaneously minimizing the formation of side products

stemming from different NO₃RR pathways and the HER. This ultimately leads to the achievement of high FEs for NH₃ synthesis. Recently, scientists have dedicated considerable effort



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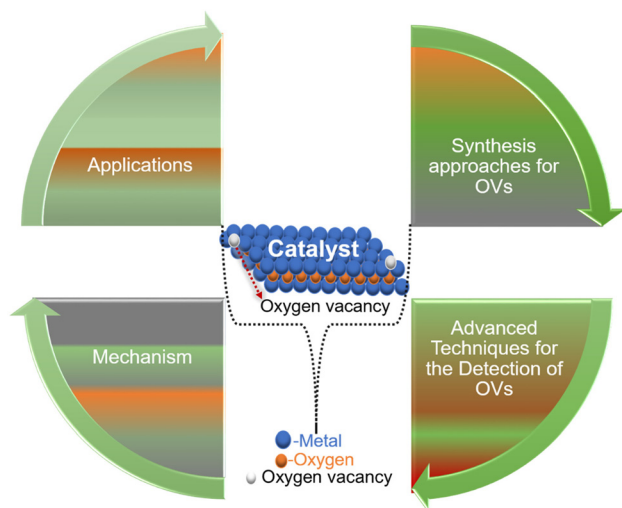
towards devising and fabricating electrocatalysts for use in the electrochemical NO_3RR to enable efficient NH_3 synthesis, making it a recent area of intense interest in the field of electrocatalysis.^{38–40} The effectiveness of the electrocatalysts commonly used is impeded by the complex eight-electron reduction process and the synchronized occurrence of the HER, which poses a competitive challenge.²⁰ This limits their selectivity and efficiency in producing ammonium from NO_3^- electroreduction. As a result, there is a pressing need to devise a new approach for creating highly efficient electrocatalysts that can selectively produce ammonium during NO_3^- electroreduction. Considerable endeavors have been directed toward creating advanced metal electrode materials by incorporating heteroatoms/heterojunctions,^{41–43} and introducing noble metals.^{7,44,45} Recent investigations have demonstrated that the inclusion of vacancy sites, such as selenium-vacancy, S-vacancy, and oxygen vacancy (OV), within materials based on metal oxides presents a straightforward and efficient approach for boosting their catalytic effectiveness.^{46–51} The incorporation of OVs as a strategy has found extensive application in diverse fields, including the OER,^{52,53} ORR,^{54,55} CO_2RR ,^{56,57} HER^{58,59} and NRR,^{60,61} supercapacitors,⁶² and batteries,^{63,64} with impressive results showcasing their remarkable ability to adsorb and activate various molecules like O_2 , H_2O , and H_2 , among others. Similarly, in the case of electrochemical nitrogen fixation, OVs can function as active sites by delivering electrons into the anti-bonding orbitals of nitrogen molecules, facilitating their adsorption and activation. Studies have documented this phenomenon, highlighting the roles of OVs in the regulation of the electronic makeup and their impact on the adsorption of electrochemical reaction intermediates.^{65–67} When combined with metal cations, neighboring OVs can act as unsaturated active sites, enabling the adsorption and weakening of N–O bonds, thereby boosting NO_3^- reduction.⁶⁸ Hence, a comprehensive exploration of the impact of OVs on the electrocatalytic NO_3RR and its intermediates is imperative to guide the design of catalysts with superior catalytic performance.

Our review covers the literature on the use of metal oxides as electrocatalysts, specifically focusing on the OVs for the NO_3RR to NH_3 up to June 2023. The purpose of this review is to show the advantages and possibilities that OVs offer to catalysis due to their enhanced morphology and the possibility of active sites on the surface of metal oxides.

Previous review articles that consolidate the utilization of oxygen vacancies (OVs) in metal oxides often exhibit a more limited focus. These reviews primarily delve into particular metal categories or applications distinct from those discussed in this comprehensive review article. For example, Jiang *et al.* investigated the influence of OVs in enhancing the photocatalytic CO_2 reduction reaction.⁶⁹ In a recent review article, Wang and co-authors conducted an extensive examination of the formation and characterization of OVs in metal oxides. Nevertheless, this paper lacks in-depth coverage of the practical applications of OVs in catalytic processes.⁷⁰ On a similar note, Lin *et al.* directed their attention toward the analysis of

oxygen vacancies within rare earth CeO_2 , a catalytic material extensively applied across diverse fields.⁷¹ Additional research from various teams encompasses a wide range of organic transformations, exemplified by processes like CO oxidation and water–gas shift reactions. These instances are used to showcase the pivotal role of the metal oxide interface in catalytic activity.⁷² Wang *et al.* provide a comprehensive review, critically examining the role of oxygen vacancies (OVs) in metal oxide photoelectrodes for photoelectrochemical water splitting.⁷³ Furthermore, Singh *et al.*⁷⁴ studied the approaches to control the concentration of OVs during the growth of metal oxides and the mechanism by which these vacancies affect catalytic reactions. They also explore the regeneration of OVs in aged catalysts and their role in the regeneration of electrocatalytic activity for CO_2 reduction. However, the precise role played by oxygen vacancies (OVs) in a diverse array of nanocatalysts during the electrochemical conversion of nitrate to ammonia lacks prior documentation. This review paper brings together recent progress in the realm of catalysts enriched with oxygen vacancies, offering an in-depth exploration of their specific contributions to the electrochemical reduction of nitrate to NH_3 . Furthermore, we placed particular emphasis on the various techniques utilized to create oxygen vacancies (OVs), advanced methods for characterizing these vacant sites, and delved into the comprehensive role that OVs play in the electrochemical nitrate reduction reactions.⁶⁷

Taking into consideration the significant role of OVs in electrochemical reduction reactions, we have consolidated the most recent research on catalysis involving OVs in this comprehensive review. Our focus in this paper specifically centers on defect metal electrocatalysts for the electrochemical reduction of NO_3^- to NH_3 . Furthermore, we have provided a concise overview of the catalytic mechanism underlying the heightened activity of OVs in NO_3^- reduction reactions. Additionally, we have outlined prospective advancements, challenges, and potential developments associated with the utilization of OVs in electrochemical NO_3^- reduction. To the best of our knowledge, a comprehensive review dedicated to the electrochemical conversion of NO_3RR to NH_3 is lacking in the literature. In this review, we will summarize recent advances in the case of catalysts composed of oxygenated architectures; the injection of ample OVs has been discovered to enhance the catalytic activity of NO_3RR by controlling the coordination environment and local electronegativity. This review offers a thorough description of current developments in the identification, processing, mechanisms, and use of OVs for NO_3RR in Scheme 1. We highlight different OV generation processes, such as wet chemical procedures, high-temperature hydrogen reduction, vacuum annealing, plasma treatment, and ion doping techniques, as well as the associated assessment methodologies. Finally, we insight opportunities and challenges associated with designing OVs in oxide-based catalysts for the NO_3RR , aiming for the rapid progress of the efficient electrocatalysts and a prosperous future of a sustainable vector of ammonia generation.



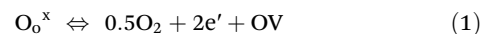
Scheme 1 The general overview covering the outlines of this review.

2. The electronic structure fingerprint of oxides: unseen actors (oxygen vacancies in metal oxides)

OVs have long remained imperceptible agents that exist on oxide surfaces. While their presence and characteristics were acknowledged, their visibility and reactivity could not be directly observed. However, a groundbreaking milestone was achieved by Flemming Besenbacher and colleagues,⁷⁵ who investigated the surface migration of OVs on TiO₂ using scanning tunneling microscope (STM) images (Fig. 2a–c). This breakthrough marked the first instance where the migration of OVs was examined in such detail. Through successful tracking of this dynamic phenomenon, the researchers unveiled that short-lived O₂ molecules facilitate the movement of OVs. These adsorbed O₂ molecules diffuse throughout the surface, actively seeking vacancies. Upon locating a vacancy, they undergo dissociation to occupy the vacancy, generating an O atom that subsequently adheres to the nearest Ti atom. Defect engineering, which involves introducing surface defects into solids, specifically metal oxides, has gained widespread application in modifying electrode materials' electronic structure and surface properties. A wide array of defects and irregularities have been extensively reported in the existing literature to date.⁷⁶ Among these, OVs are the most common and can serve as a distinctive characteristic of the electronic configuration of metal oxides.^{46,77,78} We shall examine magnesium oxide (MgO) as an example to elaborate on the electronic arrangement upon OV induction. In MgO, the absence of an O atom within the bulk or on the surface leads to the confinement of two electrons within the central void (as depicted in Fig. 2d).⁷⁹ The Madelung potential of this profoundly ionic crystal serves as the driving factor behind localizing the electrons within the void. Consequently, in the defective crystal, the position typically occupied by the O₂[−] anion in the regular lattice is substi-

tuted by two “free” electrons. The presence of trapped electrons at an OV in MgO leads to distinct excitations within the visible range of the electromagnetic spectrum. As a result, the color of the defective material undergoes a noticeable alteration, as depicted in Fig. 2e and f. These centers are commonly referred to as F centers, deriving their name from “Farbe”, the German term for color, due to their significant role in coloration phenomena. OVs are characterized by a small hollow area within the oxide matrix, which arises when an oxygen atom is extracted from its atomic-scale structure. The metal–oxygen interaction in their native lattice site causes the liberated oxygen atom to remain in a neutral state instead of being ionized. Consequently, the vacancy site retains two electrons, leading to an excess electron density on neighboring metal cations, thereby reducing their valence states (Fig. 2g and h).^{77,80} Recent research has shown that OVs in metal oxides hold great potential as a platform for the selective capture and conversion of ions in electrochemical systems. The key attributes of this approach include quicker electron transfer and stronger contact with the oxygen atom from the target species.^{81,82}

By considering factors such as the Gibbs free energy (ΔG_f), mass and balance charge, and lattice site availability, the formation of OVs can be anticipated using the following reactions.⁷⁰



The expressions used in the Kröger–Vink notation, where O_o^x represents a neutral divalent oxygen ion, e^- for an electron, and OV denotes an oxygen vacancy (with single OV and double OV denoting the charge state of ⁺¹ and ⁺², respectively), are utilized to predict the formation of OVs.⁸⁶ The conditions that govern the interaction between the lattice of the metal oxide and the presence of atmospheric oxygen during the different reaction conditions have a significant influence on the equilibrium of various defect types. The relationship between the concentration of OVs and the partial pressure of oxygen could be determined by investigating the ΔG_f and equilibrium constant (K) of the defect reaction, as shown in eqn (4).^{37,86}

$$K = \frac{[\text{V}_\text{O}] \times p(\text{O}_2)^{0.5}}{[\text{O}_\text{o}]} = \exp\left(\frac{-\Delta G_f}{K_B T}\right) \quad (4)$$

Eqn (4) demonstrates that when OVs are created, lattice oxygen atoms are discharged from the oxide matrix in the form of O₂ molecules (gas). As per the aforementioned equation, the formation of a defect site becomes more favorable under low-oxygen partial pressures. This principle has been extensively used in the development of OVs using diverse techniques.

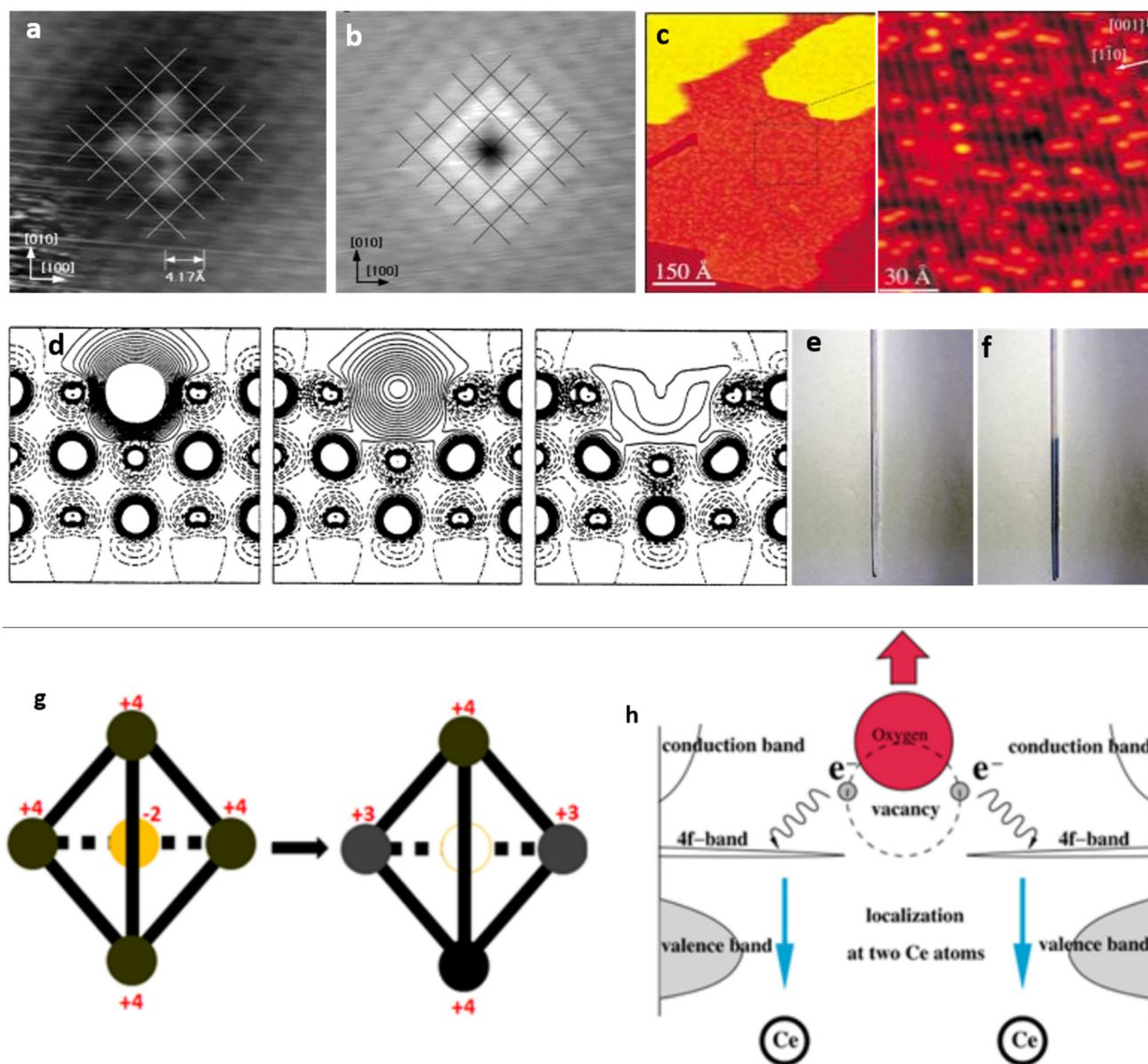


Fig. 2 (a and b) Scanning tunneling microscopy (STM) images indicating the empty state (a) and filled states (b) on a NiO(100) surface, disclosing the availability of vacancies. Reproduced from ref. 83 with permission from the American Physical Society, copyright 2022. (c) STM observation illustrating OVs as bright spots on the surface of TiO₂. Reproduced from ref. 77 and 75 with permission from Wiley, copyright 2003. (d) Electron density difference plot showing different OV configurations at the surface of MgO: left, a neutral OV with 2 trapped electrons forming an F center; a charge vacancy with 1 trapped electron forming an F⁺ center; and a doubly charged oxygen without trapped electrons forming an F²⁺ center. Reproduced from ref. 79 with permission from the American Association for the Advancement of Science, copyright 2002. (e and f) Two samples of polycrystalline MgO powder showing low (e) and high (f) concentrations of trapped electrons, resulting in significant color changes. Reproduced from ref. 77 with permission from Wiley, copyright 2003. (g) The structure of CeO₂ consists of an oxygen atom at the center surrounded by four Ce atoms forming a tetrahedron. The process of reduction shown by the arrow leads to a neutral O vacancy at the center of the tetrahedron (empty circle) while two of the Ce ions have been reduced to the +3 oxidation state. Reproduced from ref. 85 with permission from IOP, copyright 2010. (h) The formation of an OV in Ce involves the release of an oxygen atom from its lattice position, leading to the localization of two electrons on the two Ce atoms and the reduction of Ce ion oxidation states from 4⁺ to 3⁺. Reproduced from ref. 40 with permission from IOP, copyright 2002.

3. Advanced characterization techniques for the detection of OVs

Directly imaging the atomic-level lattice cave poses a significant challenge because an OV serves as a virtual object repre-

senting the oxygen lattice site in a crystal. However, there are alternative methods to indirectly characterize OVs by examining the changes they bring in the structure or electronic state, as the production of OVs can alter the electronic configuration and coordination of the surrounding metals, which can serve as a unique identifier for the OVs in metal oxides.^{77,87} For

instance, the STM (scanning tunneling microscope) can be used to visualize the OV caves,^{88,89} while PAS (positron annihilation spectroscopy) can be used to monitor them.^{90,91} Moreover, the XRD, ND (neutron diffraction), and XAS (X-ray absorption spectroscopy) techniques can detect changes in the crystalline structure caused by OVs.^{92,93} XPS (X-ray photoelectron spectroscopy), EPR (electron paramagnetic resonance) spectroscopy, PL (photoluminescence) spectroscopy, and XAS (X-ray absorption spectroscopy) can be used to modify the electronic property.⁷⁷ A recent publication has discussed the various pathways available for characterizing OVs, which are illustrated in Fig. 3.⁷³ In this paper, our attention is directed toward the commonly employed effective strategies: XPS, EPR, and XAS.

3.1 X-ray absorption spectroscopy (XAS) technique

The characterization of OVs encompasses the investigation of changes in the electronic configuration and crystalline structure, requiring a detailed analysis of alterations in the electronic distribution and the arrangement of atoms within the crystal lattice. The chemical changes can be analyzed by using the XPS and EPR techniques, while both feature electronic and structural properties can be analyzed with XAS. The interaction of X-ray photons with core electrons in atoms gives rise to a distinctive peak in the absorption intensity at a particular energy level, which is referred to as the absorption edge. XAS can be categorized into two distinct groups depending on the

absorption range; XANES (X-ray absorption near edge structure) covers the absorption region from the edge up to several tens of electrons volts (eV), while extended X-ray absorption fine structure (EXAFS) includes the absorption range from the edge to several hundreds of eV.⁹⁴ XANES can provide information about the extent of orbital occupation, specifically the number of electrons occupying a particular orbital. For instance, the study of oxygen deficiency in CaMnO_3 (Fig. 4b) has revealed an apparent decrease in the chemical state of Mn through Mn L_{2,3}-edge analysis.⁹⁵ Additionally, the formation of OV generates energy levels of oxygen defects in the band gap, resulting in changes to the XANES of the O K-edge. This phenomenon is demonstrated in Fig. 4c, which illustrates the change in the O K-edge of HfO_2 where OV induces a reduction in electron occupation and a band tail near the conduction band edge (inset Fig. 4). Zhu and his team⁹⁶ conducted an investigation using XANES analysis to explore the structural defects in $\text{Vd-V}_2\text{O}_3$. The results revealed that the V component in $\text{Vd-V}_2\text{O}_3$ has a higher oxidation state than $\text{c-V}_2\text{O}_3$, as indicated by the edge spectra observed at the B-site in Fig. 4f. The presence of vanadium vacancies in $\text{Vd-V}_2\text{O}_3$ might contribute to the elevated levels of V^{4+} , increasing the oxidation state of vanadium. As depicted in Fig. 4f (site A), the intensified pre-edge band indicates a reduction in the local symmetry in the $\text{Vd-V}_2\text{O}_3$ sample. This observation suggests that the structure of $\text{Vd-V}_2\text{O}_3$ experiences distortion around the vanadium atoms due to the lack of neighboring atoms. In contrast to XANES,

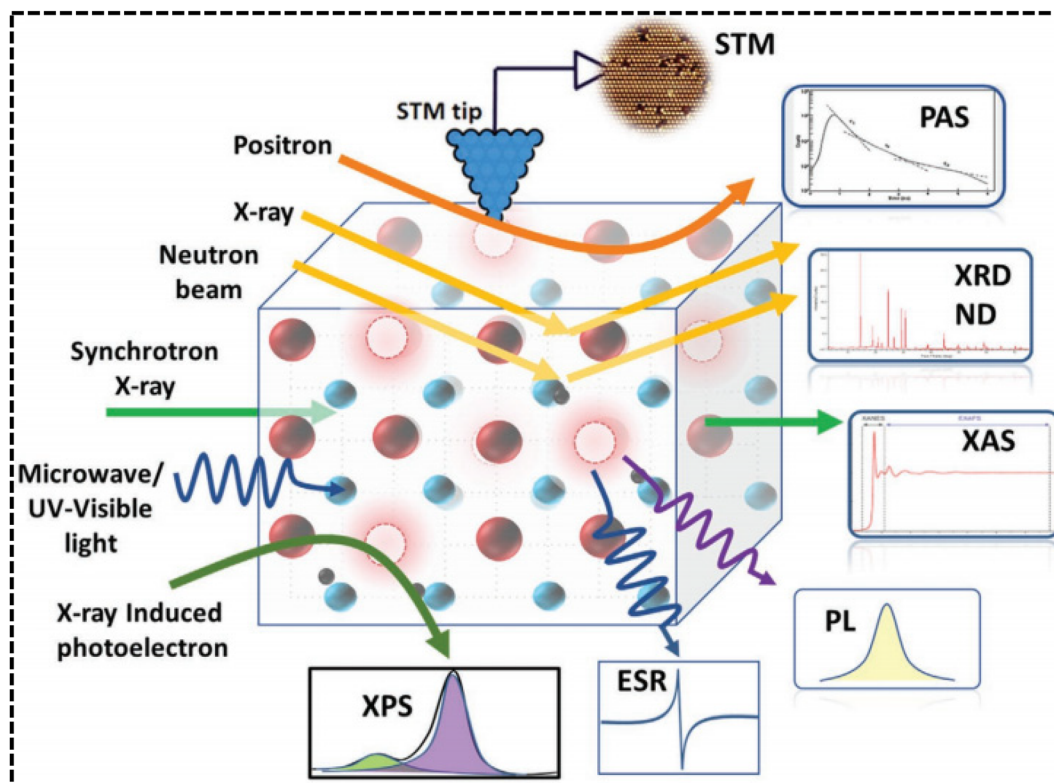


Fig. 3 A characterization technique used for the detection of OV. Reproduced from ref. 73.

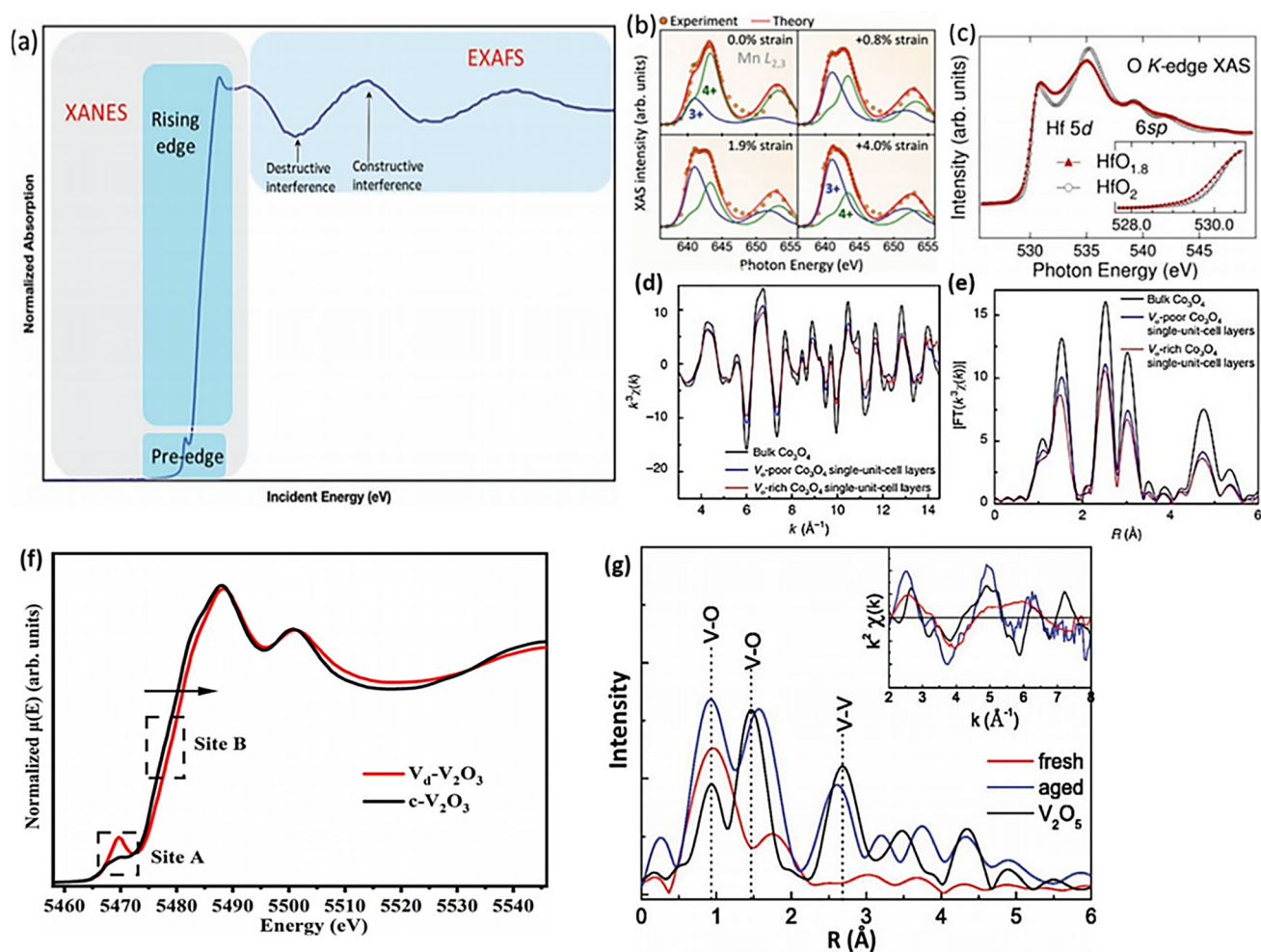


Fig. 4 Presents various XAS analyses used for characterizing OV in metal oxides: (a) the typical profile of the XAS. Adapted with permission.⁹⁴ (b) The XANES of a Mn L-edge under different strains. Reproduced from ref. 95 with permission from the American Chemical Society, copyright 2017. (c) The XANES of an O K-edge of HfO₂ with OV. Reproduced from ref. 97. (d) and (e) EXAFS oscillation and the corresponding Fourier transforms of VO-rich Co₃O₄ and VO-poor Co₃O₄ single-unit-cell layers. Reproduced with permission.⁹⁸ (f) Normalized XANES spectra of a V K-edge for Vd-V₂O₃ and c-V₂O₃. (g) The FFT of k^2 -weighted EXAFS of a V L-edge for different V₂O₅ samples. Reproduced from ref. 99 with permission from AIP, copyright 2014.

EXAFS offers a more direct means of understanding changes in the crystalline structure of OV, such as variations in M–O bond length and M coordination number. When OV is produced in metal oxides (MOs), the crystal structure may undergo relaxation, which can alter the nearby M–O bond. Utilizing k^2 -weighted EXAFS and subsequent fast-Fourier transforms (FFT), by examining the magnitude and relative distance of interatomic forces, it becomes feasible to calculate the average number of nearest neighbors and the interatomic distances, respectively.⁹⁷ As an illustration, Gao *et al.*⁹⁸ obtained a Co₃O₄ sample rich in OV by calcining a Co precursor at 320 °C in an air environment. The EXAFS analysis, shown in Fig. 4d and e, unveiled the significant concentration of V_O and indicated a decrease in the coordination number of Co–O bonds in the V_O-rich Co₃O₄ material. Another research study on V₂O₅ film found that the recently manufactured sample had much weaker V–O bonds than the conventional V₂O₅, suggesting that

the presence of OV inhibited V–O bond formation. However, the OV defect was restored with aging, leading to a significant increase in V–O bond strength. (Fig. 4g).⁹⁹

3.2 Electron paramagnetic resonance (EPR) method

In the characterization of OV, the electron that is compensated in OV can exhibit different behaviors depending on the concentration of OV and the temperature. Metal ions can entrap it or position it close to the OV, leading to changes in the electron spin state of MOs, and this causes the magnetron to react to an external field.¹⁰⁰ Therefore, using the EPR technique can be an excellent method for detecting the presence of OV with high accuracy and sensitivity.^{101,102} Electron spin resonance (ESR) spectroscopy, also known as EPR spectroscopy, was utilized to detect OV signals in several different types of material. For example, in FTO-E (Fe₂TiO₅) prepared by the electrospinning method and FTO-H (Fe₂TiO₅) prepared by

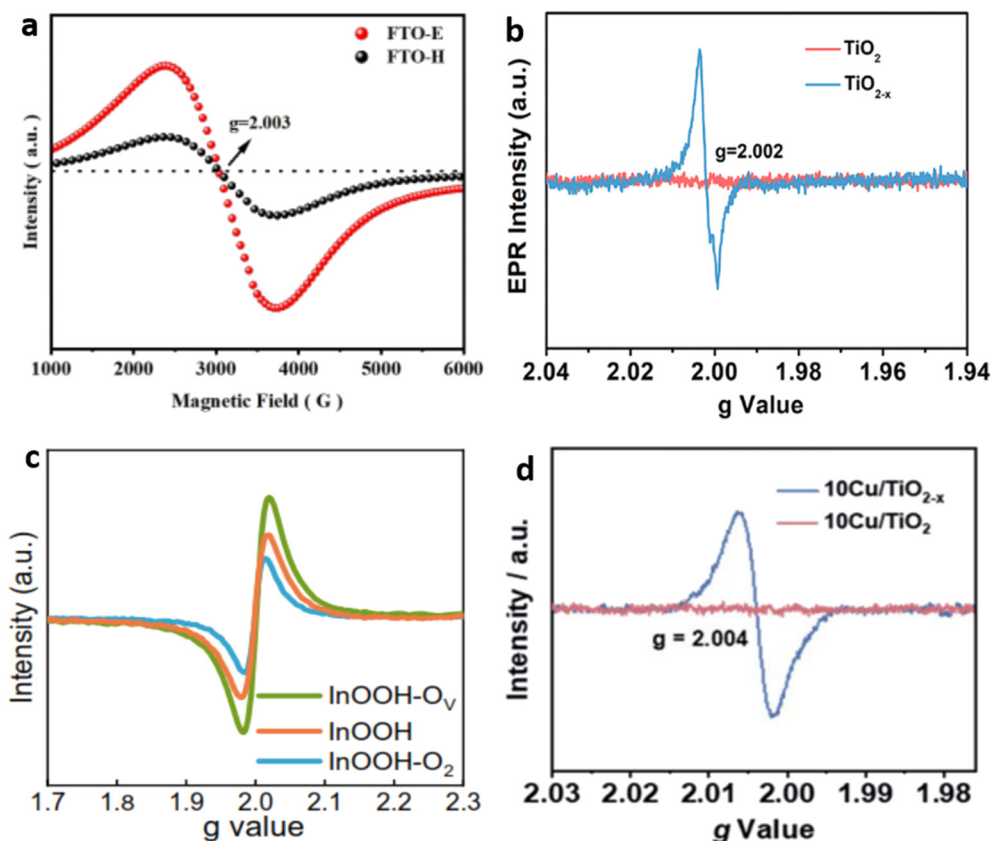


Fig. 5 Displays the EPR spectra of (a) FTO prepared by electrospinning and hydrothermal methods. Reproduced from ref. 103 with permission from Wiley, copyright 2022. (b) Pristine TiO_2 and TiO_{2-x} nanotubes. Reproduced from ref. 105 with permission from the American Chemical Society, copyright 2020. (c) Indium oxyhydroxide with different vacancies. Reproduced from ref. 22, and (d) Cu cluster deposited TiO_2 . Reproduced from ref. 106.

the hydrothermal method), the ESR signal exhibited peak values at $g = 2.003$, indicating the presence of OVs^{103,104} (Fig. 5a). Additionally, the larger magnitude of the ESR signal in FTO-E suggests that higher concentrations of OVs are generated in this sample compared with FTO-H. Similarly, the EPR spectroscopic technique has also been utilized to successfully detect the formation of OVs in various materials such as TiO_2 nanotubes,¹⁰⁵ Cu cluster TiO_2 ,¹⁰⁶ and indium oxyhydroxide (InOOH-OV) (Fig. 5b–d).²²

3.3 X-ray photoelectron spectroscopy (XPS) analysis of the detection

XPS proves to be a highly effective and precise method for measuring the presence of defect sites in solid material. XPS measurements can be used to observe the shift in M–O bonding energy caused by the presence of OVs in a material.^{107,108} The formation of OVs can result in charge compensation, leading to the reduction of metal ions and the subsequent formation of low-valence metal ions. This phenomenon is illustrated in the XPS spectra of the Mo 3d and O 1s of $\text{OV-MoO}_3/\text{Ce}$ samples.¹⁰⁹ Upon the inclusion of OVs through Ce doping, the binding energy of Mo in the $\text{OV-MoO}_3/\text{Ce}$ spectra demonstrates a declining pattern, suggesting the reduction of some Mo^{6+} to Mo^{5+} . The ratio of Mo^{5+} to Mo^{6+}

gradually increased with the increasing amount of Ce doping, as illustrated in Fig. 6a, c, e, and g of the Mo 3d XPS pattern. The content of Mo^{5+} is considered a reliable indicator of the relative abundance of OVs; thus, a higher Mo^{5+} content corresponds to a greater amount of OVs. The O 1s spectrum further confirmed this result (Fig. 6b, d, f, and h). The presence of a prominent peak at 531.8 eV in $\text{OV-MoO}_3/\text{Ce}$, in contrast to OV-MoO_3 , signifies the higher concentration of OVs in the $\text{OV-MoO}_3/\text{Ce}$ sample.⁵⁷ The high-resolution X-ray photoelectron spectra (HRXPS) of In 3d and O 1s of InOOH showed a similar pattern,²² where the peak for In 3d_{5/2} at 444.2 eV in InOOH moves down in binding energy after being exposed to Ar plasma and up in binding energy after being exposed to O_2 plasma (as shown in Fig. 6i). This change shows that InOOH-OV has the lowest indium valence of the samples tested.^{110,111} The O 1s XPS data exhibited three peaks, at 529.8, 531.5, and 532.8 eV, which corresponded to the oxygen lattice (OL), OVs, and hydroxyl groups from adsorbed water, respectively, as depicted in (Fig. 6j).^{112,113} Following Ar plasma treatment, the proportion of OV increases significantly to 40.9% in InOOH-OV , while the OL percentage drops to 19.9%, indicating that lattice oxygen atoms have been removed. In another example, the Co^{2+} and Co^{3+} ratio in Co_3O_4 was also examined before and after plasma treatment.⁶⁰ The deconvoluted Co 2p

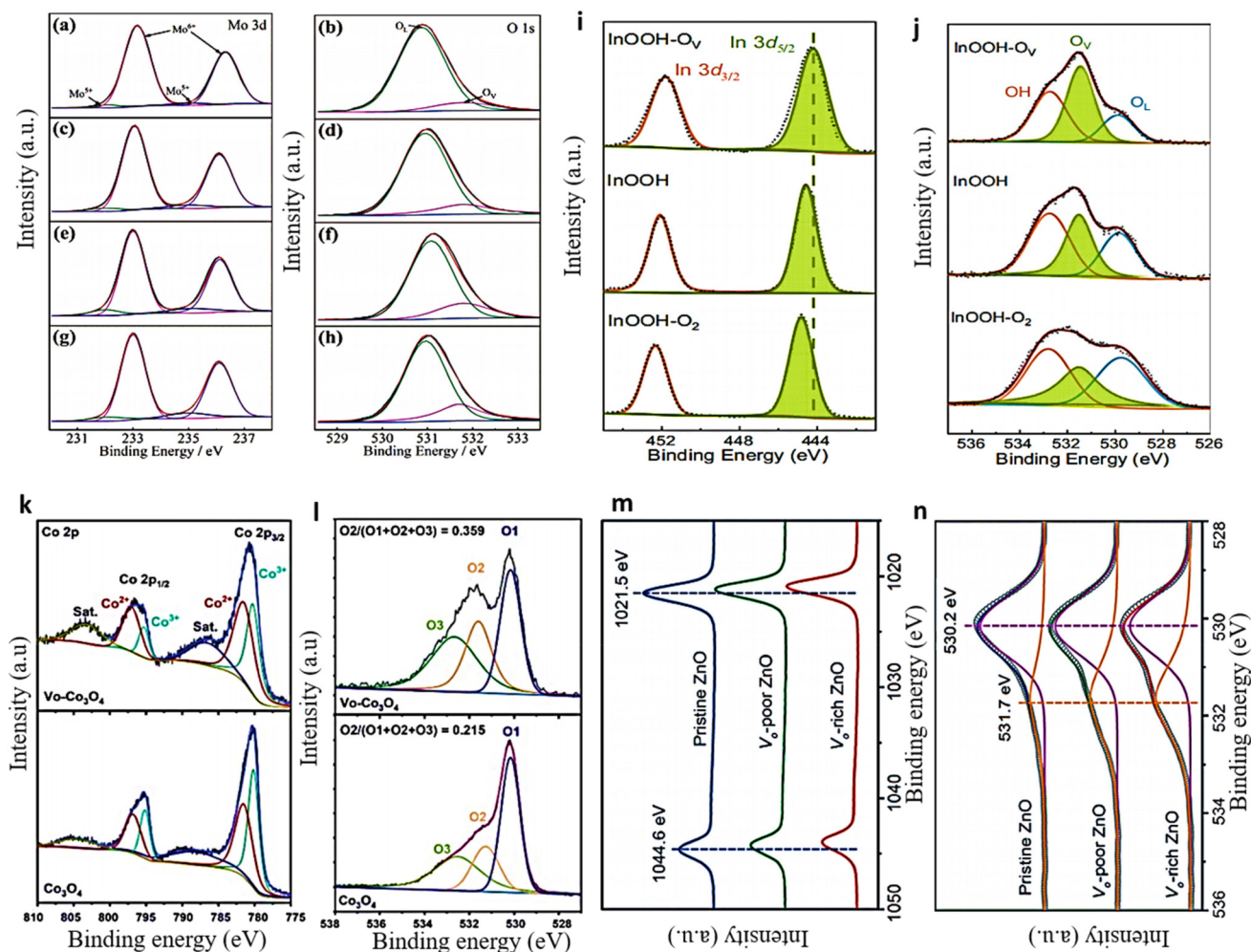


Fig. 6 (a and b) Mo 3d and O 1s deconvolution using XPS in OV-MoO₃. 1 (c and d) XPS analysis of OV-MoO₃/Ce = 40/1 indicates 0.62% doped, (e and f) OV-MoO₃/Ce = 30/1, and (g and h) OV-MoO₃/Ce = 20/1, respectively. Reproduced with permission.¹⁰⁹ (i and j) The corresponding HR-XPS spectra of 3d and O 1s of InOOH. Reproduced with permission.²² (k and l) VO-Co₃O₄ and Co₃O₄ Co 2p and O 1s XPS spectra. Reproduced with permission.⁶⁰ (m and n) Zn 2p and O 1s XPS spectra of ZnO nanosheets. Reproduced from ref. 111 with permission from Wiley, copyright 2018.

spectra demonstrate an increase in the intensity of Co²⁺ and a decrease in the intensity of Co³⁺ after plasma treatment (as shown in Fig. 6k). The Co²⁺/Co³⁺ ratios were determined to be 1.48 for VO-Co₃O₄ and 1.10 for Co₃O₄, respectively. The high proportion of Co²⁺ observed in Co₃O₄ following plasma treatment suggests the occurrence of OV generation. The O 1s deconvoluted spectrum revealed the presence of three oxygen species. O₁ at 530.1 eV is associated with the typical M–O bond, while O₂ at around 531.3 eV and O₃ at 532.6 eV are linked to the OVs and adsorbed water, respectively.¹¹⁴ After plasma treatment, oxygen defects are formed, as evidenced by an increase in oxygen content (from 0.215 to 0.359) and a shift in the O₂ peak to a higher binding energy of 531.6 eV (as shown in Fig. 6l). Likewise, the presence of OVs in ZnO nanosheet samples was detected, revealing that the binding energies of Zn (2p_{1/2} and 2p_{3/2}) decreased as the concentration of OVs increased in the three ZnO nanosheets¹¹¹ (as depicted in Fig. 6m). The material's O 1s spectra exhibited an

OV peak at 531.7 eV,¹¹⁵ which was particularly prominent in the sample with a high concentration of OVs (Fig. 6n).

3.4 Positron annihilation spectroscopy (PAS)

In the realm of porous materials research, there has been a significant surge of interest in PAS in recent times.^{91,116} Fig. 7a illustrates a direct approach for detecting cavities in metal–organic framework materials.¹¹⁷ By interacting with the material matrix, positrons can recombine with electrons. The varying pore sizes within the material will induce distinct positron decay practices, consequently resulting in diverse time-resolved decay patterns, as depicted in Fig. 7b. Given that those vacancies (OVs) are also considered types of cavity within crystals, there is an interest in utilizing PAS to detect these OVs.^{118,119} Recent work has used PAS to examine VO in TiO₂ samples synthesized at 350 °C and 550 °C (denoted m-350 and m-550, respectively).¹¹⁹ Fig. 7c demonstrates two types of positron lifetime, τ_1 and τ_2 , which correspond to different defects

found in the samples. The smaller lifetime (τ_1) is associated with OV defects, while the larger lifetime (τ_2) broadly indicates the existence of micro-pore defects.¹²⁰ Approximately 96% and 74% of τ_1 may be found in the m-350 and m-550 samples, respectively. These results point to OV flaws as the predominant source of failure in m-350 and m-550. Another study also observed a comparable pattern in the PAS analysis of $\text{Bi}_{24}\text{O}_{31}\text{Br}_{10}$ samples (BOB),⁹¹ and the findings are illustrated in Fig. 7d. It is important to acknowledge that the interpretation of PAS can vary, as stated by the authors of this study, who mention that both pore sizes and grain boundaries can influence the positron decay process. Furthermore, various types of defect, such as metal vacancies, can yield similar results in PAS, as illustrated in Fig. 7e.¹²¹ In a specific investigation of the BiVO_4 system utilizing PAS, as depicted in Fig. 7f, the characteristics of vanadium vacancies, as opposed to VO vacancies, have been identified.¹²² PAS allows for the quantifi-

cation of the charge distribution associated with these vanadium vacancies.

4. Commonly used methodologies for the creation of OVs

The abundance of active sites primarily influences the electrochemical properties of electrode materials. Although many materials possess a significant surface area, certain regions within them remain electrochemically inert, impeding the transfer of small molecules or ions. These regions are commonly referred to as inert sites. By employing strategic defect engineering, it is possible to manipulate the chemical environments of these inert sites, rendering them accessible for rapid reaction kinetics.⁷⁶ Multiple techniques have been employed to induce the formation of oxygen vacancies in metal oxides,

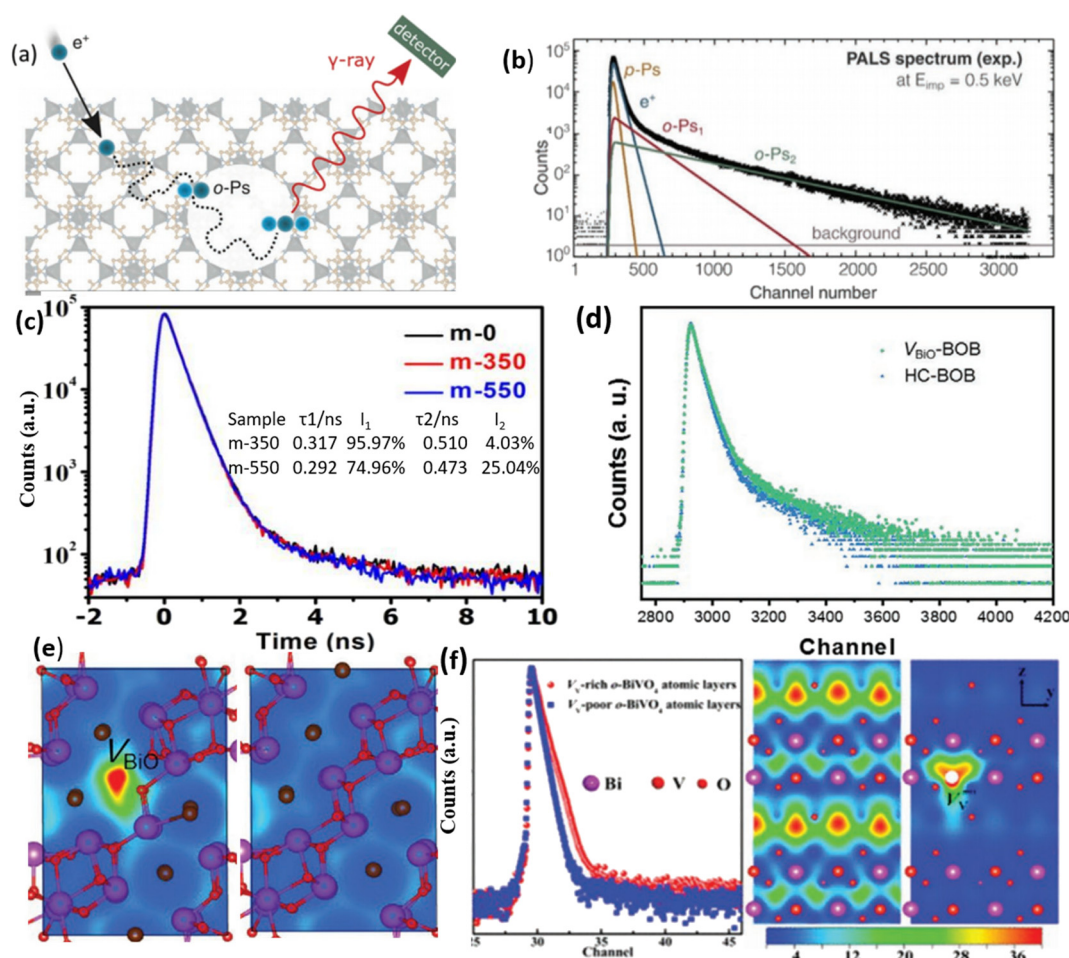


Fig. 7 (a) Positron annihilation model depicted schematically within a porous cave. (b) Analysis of the PAS spectrum and fitting of various degradation processes. Reproduced from ref. 117 with permission from Wiley, copyright 2021. (c) These are the positron annihilation spectra of samples of m-0, m-350, and m-550. The findings of the positron annihilation tests are displayed in the inset of figure (c); τ_1 and τ_2 are positron lifetimes; I_1 and I_2 are the concentrations of τ_1 and τ_2 . Reproduced with permission.¹¹⁹ (d) Positron annihilation lifetime spectrum of VBiO-BOB and HC-BOB , respectively. (e) Schematic representations of trapped positrons of VBiO-BOB and HC-BOB , respectively. Reproduced from ref. 91 with permission from Wiley, copyright 2021. (f) The use of PAS to characterize vanadium vacancies and the heat map that corresponds to the charge distribution around vanadium vacancies. Reproduced with permission.¹²²

either during the synthesis process or through post-synthesis treatments. In the following section, we present a comprehensive review of several noteworthy techniques employed for the formation of oxygen vacancies in different materials.

4.1 Thermal annealing

Thermal annealing performed in a vacuum or inert condition can create OVs in metal oxides.^{123,124} It is worth mentioning that the careful choice of appropriate reducing atmospheres, treatment durations, calcination temperatures, and types of working gas can control the concentration of OVs in the resulting as-calcinated metal oxide materials.^{125,126} In their study, Li *et al.*¹²⁷ prepared $\text{Bi}_2\text{O}_{3-x}$ by oxidizing Bi powder in the presence of air at a temperature of 453.15 K for 8 hours (Fig. 8a). The resulting sample demonstrated a conspicuous EPR signal at $g = 2.001$, providing evidence of the presence of OVs.^{112,128} Conversely, the Bi powder did not exhibit any EPR signal. The EPR data strongly support the hypothesis that the calcined sample contains oxygen defects, which aligns with the absorp-

tion spectra depicted in Fig. 8b. The O 1s XPS spectra provided additional support for the EPR data, as evidenced by the presence of the OV peak at 531.2 eV.¹²⁹ Notably, the peak area at 531.2 eV was significantly larger in the calcinated sample compared with the Bi powder, indicating that the oxygen vacancies were predominantly obtained through the process of heat treatment (Fig. 8c). Considering all of the aforementioned findings, after the calcination procedure, it is possible to conclude that the sample did produce unique oxygen vacancies.

Similarly, OV-C/ TiO_2 samples were synthesized by Qian *et al.*¹³⁰ by subjecting Ti_3C_2 MXene, serving as the precursor, to a single calcination step (Fig. 8d). The scientists observed that the temperature employed during the experiment influenced the number of OVs, as indicated by the findings from the XPS and EPR analyses (Fig. 8e and f). The O 1s spectra exhibited a prominent OV peak at 531.9 eV, further substantiated by an EPR signal at $g = 2.003$.^{131,132} As the calcination temperature was increased, a noticeable decrease in the peak intensity was observed, suggesting that the temperature influ-

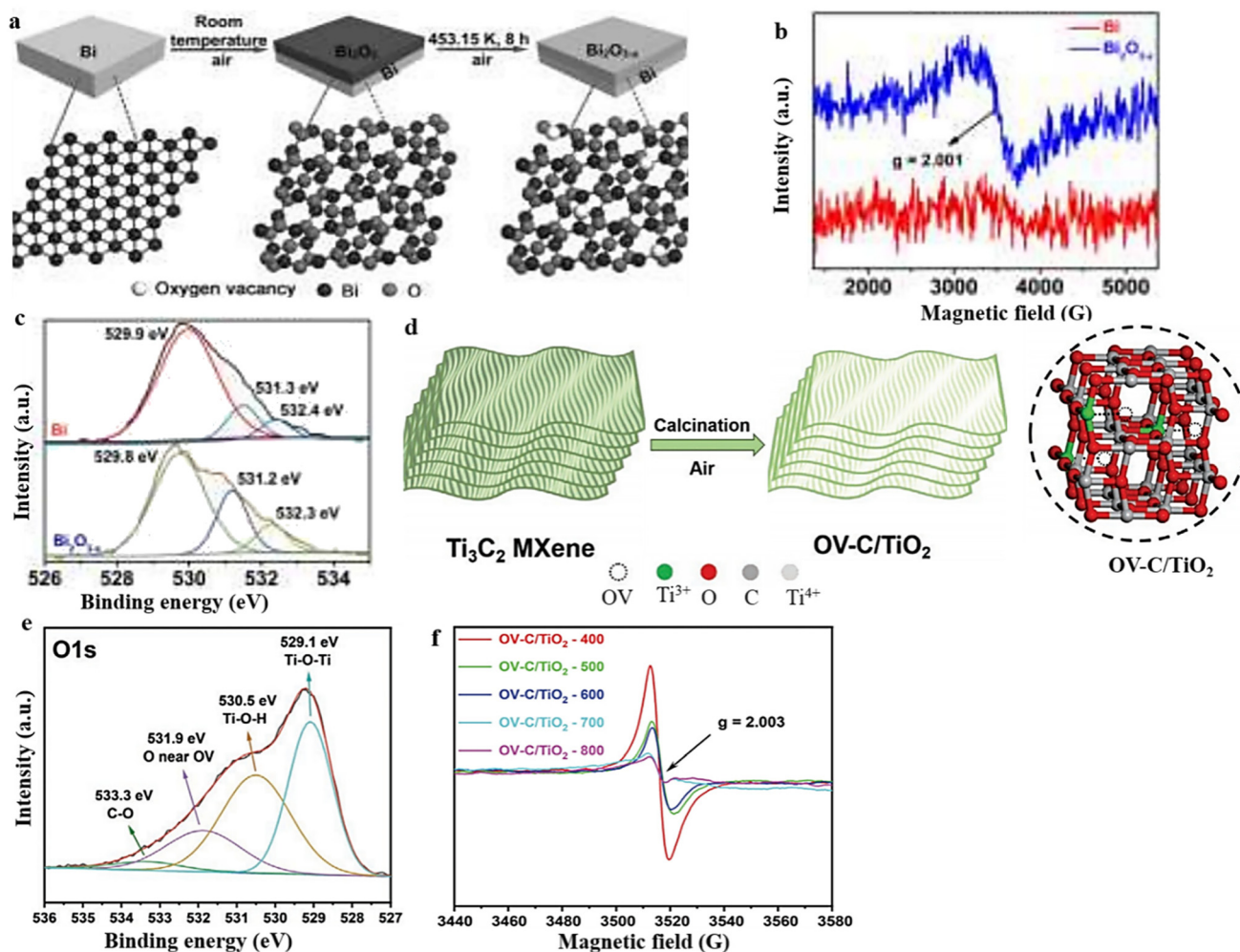


Fig. 8 (a) An illustration of the schematic process for the production of a layer of $\text{Bi}_2\text{O}_{3-x}$ with oxygen vacancies. (b) and (c) EPR and O 1s XPS spectra of $\text{Bi}_2\text{O}_{3-x}$. Reproduced from ref. 127 with permission from Wiley, copyright 2020. (d) Diagram of the preparation process of OV-C/ TiO_2 . (e) and (f) The O 1s XPS and EPR spectra of OV-C/ TiO_2 . Reproduced from ref. 130 with permission from Wiley, copyright 2021.

ences the concentration of oxygen vacancies during the calcination process. Other studies have also documented the influence of heat treatment on the generation of OV_s.^{133,134}

4.2 Plasma treatment

The effectiveness of plasma treatment in producing surface OV_s on metal oxides has been well established. During plasma treatment, OV_s are formed through the impact of energetic species (*e.g.*, Ar⁺, H₂O⁺, N²⁺) on the MO, causing the surface structure to become disordered and facilitating the controlled removal of oxygen atoms from the surface to create vacancies.^{135,136} This approach, characterized by its simplicity, high efficiency, and short experimental time, has found extensive application in generating OV_s across various materials for various purposes.^{53,137,138} To demonstrate this phenomenon, OV_s were induced on Co₃O₄ through a 2-minute treatment using Ar plasma (250 W) (Fig. 9a),¹¹⁴ while H-doped black titania (TiO₂@TiO_{2-x}H_x) enriched with OV_s was achieved by subjecting it to H₂ plasma.¹³⁹ XPS analysis and EPR investigation provided confirmation of the presence of OV_s in the samples subjected to plasma treatment (Fig. 9e and f).

4.3 Wet-chemical reduction

The wet chemical redox method offers a scalable solution for introducing OV_s into MOs under ambient conditions. This technique relies on the utilization of appropriate reducing agents and operates at low temperatures, ensuring the methodology's safety and cost-effectiveness. As an example, Liu *et al.*¹⁴⁰ demonstrated a simple and efficient chemical approach for the synthesis of oxygen-defective r-Bi₂O₃ (Fig. 10a). The method involved room temperature reduction using NaBH₄, resulting in enhanced active sites and an improved conductivity of Bi₂O₃. The O 1s XPS spectra exhibit a peak at approximately 531.8 eV, corresponding to oxygen defects in the prepared material (Fig. 10b).¹⁴¹ Compared with Bi₂O₃/GN, r-Bi₂O₃/GN exhibits a higher intensity in the oxygen-defect peak, indicating a greater induction of oxygen defects in Bi₂O₃ after reduction. In a separate investigation, the induction of surface OV_s in BiOIO₃ was achieved by treating the sample with a KI solution under continuous stirring for 14 hours at room temperature¹⁴² (Fig. 10c). The sample prepared with 0.2 × 10⁻³ M KI was denoted as BIO-LOV₂. Fig. 10d and e illustrate the identification of the created OV_s through

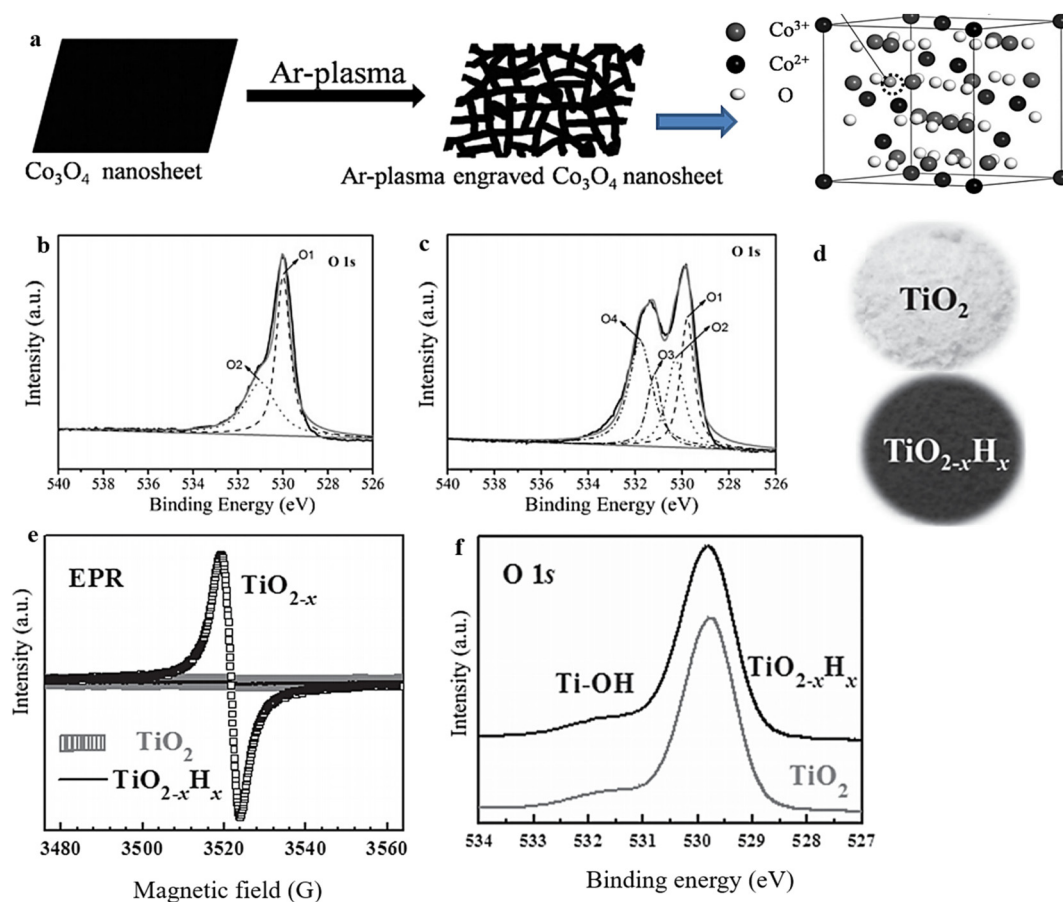


Fig. 9 (a) Illustration of the process for producing oxygen-vacancy-rich, high-surface-area Co₃O₄ that was etched using Ar-plasma. (b) and (c) XPS 1s spectra of pristine Co₃O₄ and plasma-engraved Co₃O₄ respectively. Reproduced from ref. 114 with permission from Wiley, copyright 2016. (d) Photographs of pristine TiO₂ and black titania (TiO_{2-x}H_x). (e) and (f) EPR and XPS 1s spectra of pristine and OV-rich TiO₂ samples. Reproduced from ref. 139 with permission from Wiley, copyright 2013.

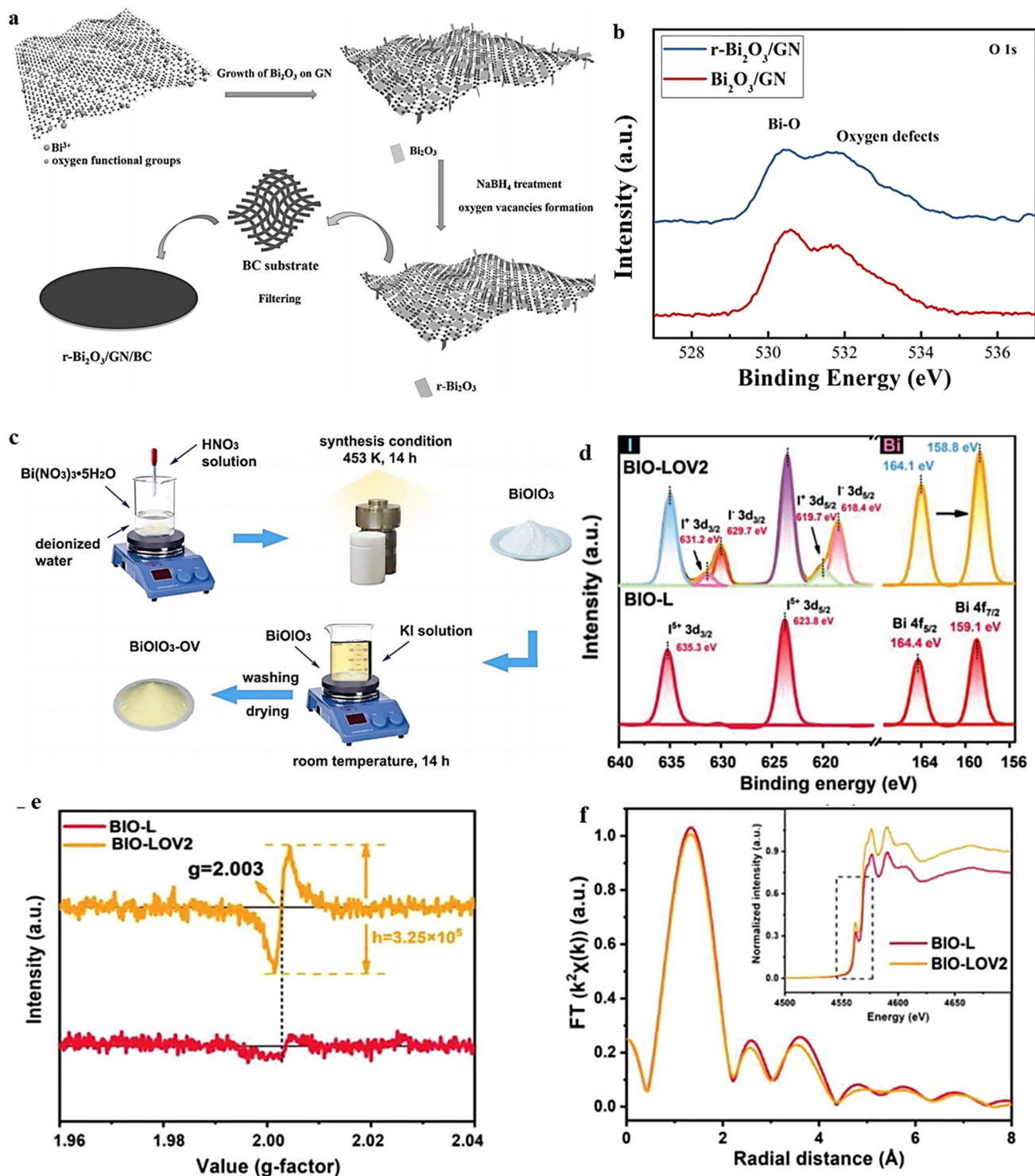


Fig. 10 (a) Schematic diagram showing the steps used to create a flexible $r\text{-Bi}_2\text{O}_3/\text{GN}/\text{BC}$ electrode during the synthesis process. (b) XPS analysis Bi-O. Reproduced from ref. 140 with permission from Wiley, copyright 2017. (c) Schematic illustration for the preparation process of BiOIO_3 and $\text{BiOIO}_3\text{-OV}$ samples. (d) The XPS of I 3d and Bi 4f. (e) EPR spectra and (f) Fourier-transform curves of EXAFS of BiO-L and BiO-LOV_2 . Reproduced with permission.¹⁴²

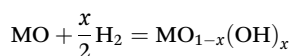
XPS and EPR analyses. The presence of lower-valence iodine ions ($\text{I}^+ 3d_{3/2}$, $\text{I}^+ 3d_{5/2}$, $\text{I}^- 3d_{3/2}$, and $\text{I}^- 3d_{5/2}$) in BiO-LOV_2 serves as evidence for the existence of OV (Fig. 10d).^{143,144}

Additionally, an XAS investigation was conducted to examine the modifications in the electronic states of the I element in the prepared samples. A notable distinction was observed

between BIO-L and BIO-LOV₂, with the I element in BIO-LOV₂ exhibiting a slight shift towards lower energy. This shift indicates a change in the valence state from I⁵⁺ to I^(5-x). The Fourier transform of BIO-LOV₂ displays a decrease in peak intensity, which can be attributed to a surface structural deformation resulting from the reduction of adjoining oxygen atoms around the I atoms (Fig. 10f). These findings follow the XPS and EPR data,^{145,146} further supporting the presence of such surface structural changes. The results above, taken together, provide evidence of the presence of surface OVVs in BIO-LOV₂. These OVVs primarily originate from a lack of O atoms within the IO₃ polyhedra.

4.4 Hydrogen treatment

Hydrogen exhibits remarkable reducing capabilities, enabling it to selectively reduce specific metal ions to a lower oxidation state while simultaneously generating OVVs in the resultant material. Compared with the thermal protocol in an oxygen-deficient condition, the hydrogenation procedure represents a simpler approach to generate OVVs and transform different metal oxides (MOs) into their respective nonstoichiometric forms, as described in the following equation;



The generation of OVVs can potentially occur through a mechanism where electrons from the reducing agent are induced into the d orbitals of metals, resulting in a significant weakening of the metal–oxide bonds.⁷⁷ As a result, the oxygen atoms have two potential routes to exit the crystal lattice: they can either form water vapor (in the presence of a hydrogen flow) or bond with metal atoms to create more stable oxides like Al₂O₃ or MgO.^{147,148} Additionally, alongside the generation of oxygen vacancies, there is a notable reduction in the metal ions. For example, in 2011, a novel black TiO₂ variant was discovered due to subjecting it to high-pressure treatment with H₂. This transformation was attributed to the formation of Ti³⁺ and OV, which reduced the bandgap (Fig. 11b and c).¹⁴⁹ Furthermore, a more rigorous treatment involving magnesium metal and H₂ flow produced oxygen vacancy ZrO.¹⁴⁷ The evident color alteration observed in the samples (white to black), the shift in the chemical state of Zr, and the bandgap reduction (as depicted in Fig. 11e and f) provide evidence for the formation of oxygen vacancies.

4.5 Electrochemical reduction

There is an ongoing debate regarding the reduction process involving the application of reducing agents in the H₂ treatment procedure. One argument suggests that when TiO₂ is

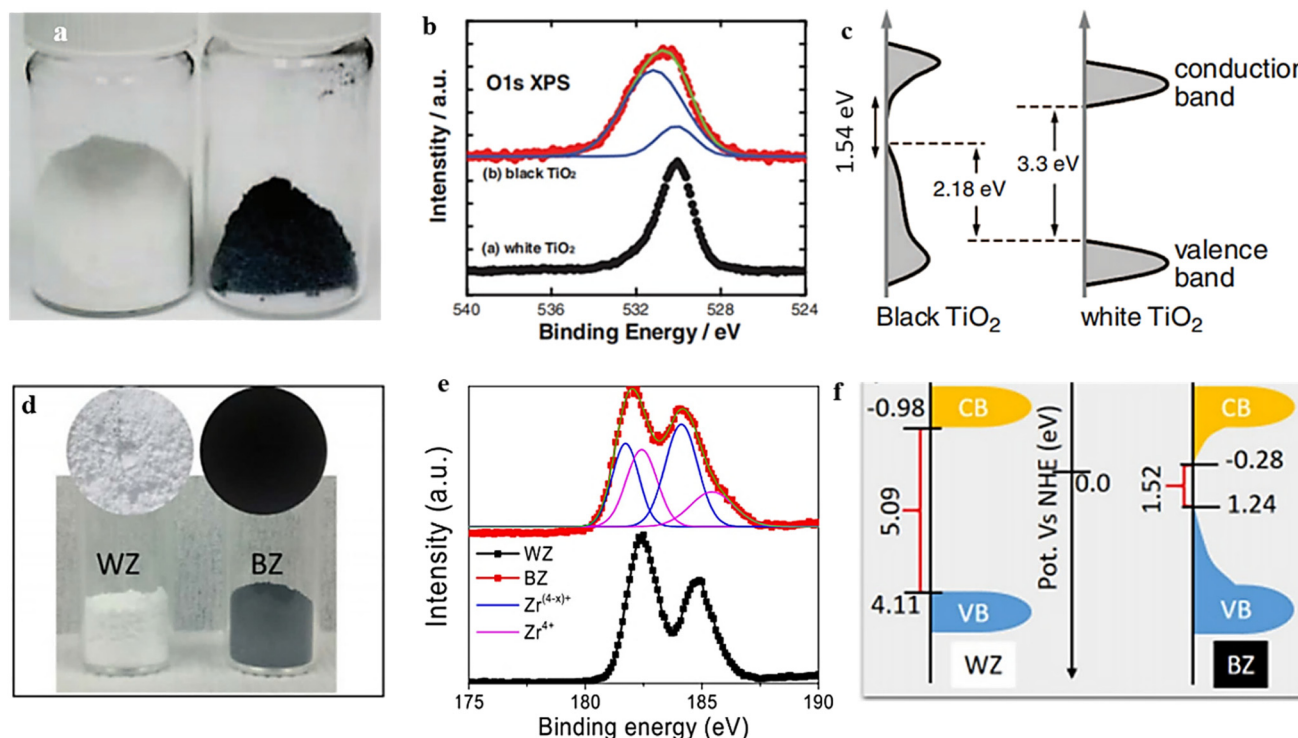


Fig. 11 (a) This image shows TiO₂ nanocrystals in their natural white and disorder-engineered black nanocrystals. (b) TiO₂ O 1s XPS spectra, both white and black. (c) Diagram comparing the DOS of disorder-engineered black TiO₂ nanocrystals with that of unmodified black TiO₂ nanocrystals. Reproduced from ref. 149 with permission from the American Association for the Advancement of the Science, copyright 2011. (d) A photograph of the powder samples, illustrating the difference in color between the white (WZ) and black (BZ) ZrO. (e) Zr 3d XPS spectra of WZ and BZ. (f) The most likely band energy diagrams of zirconia samples in black (BZ) and white (WZ) samples. Reproduced from ref. 147.

treated with hydrogen, H atoms can be inserted into its lattice, potentially creating an interstitial H (Hi) doped structure.¹⁵⁰ To circumvent any potential problems arising from reduction agents, an alternative approach is to introduce electrons directly into MOs *via* an electrochemical method. This method is commonly employed to induce OVs in MOs. The utilization of this approach provides a promising substitute that brings forth numerous benefits, including a swift reaction time, affordability, and convenient operation at lower temperatures. By manipulating electrochemical factors like voltage, reaction time, and current density during the procedure, precise control over the content of OVs in metal oxide catalysts can be achieved. Research has shown that OVs have been induced in various materials *via* electrochemical reduction protocols.^{151–153}

Guo *et al.*¹⁵⁴ successfully synthesized a wide variety of materials rich in OVs by implementing the converse voltage utilization technique. Using $\text{Co}(\text{OH})_2$ as a case study, we present an exemplified protocol to demonstrate the designed procedure in this paper. In the initial stage of the procedure, carbon paper served as a substrate for the electrochemical deposition of $\text{Co}(\text{OH})_2$ nanosheets using a voltage of -1.5 V. This step resulted in the formation of hybrids known as Co-OH (Fig. 12a). Subsequently, a converse voltage of 1.5 V was applied, producing CoOOH nanosheets with high activity and an abundance of defects. Throughout this process, the $\text{Co}(\text{OH})_2$ underwent partial oxidation and *in situ* conversion, resulting in the generation of EA-CoOOH (Fig. 12b and c), which exhibited significant oxygen vacancies and defects (Fig. 12d and e). Wang and colleagues employed a straight-

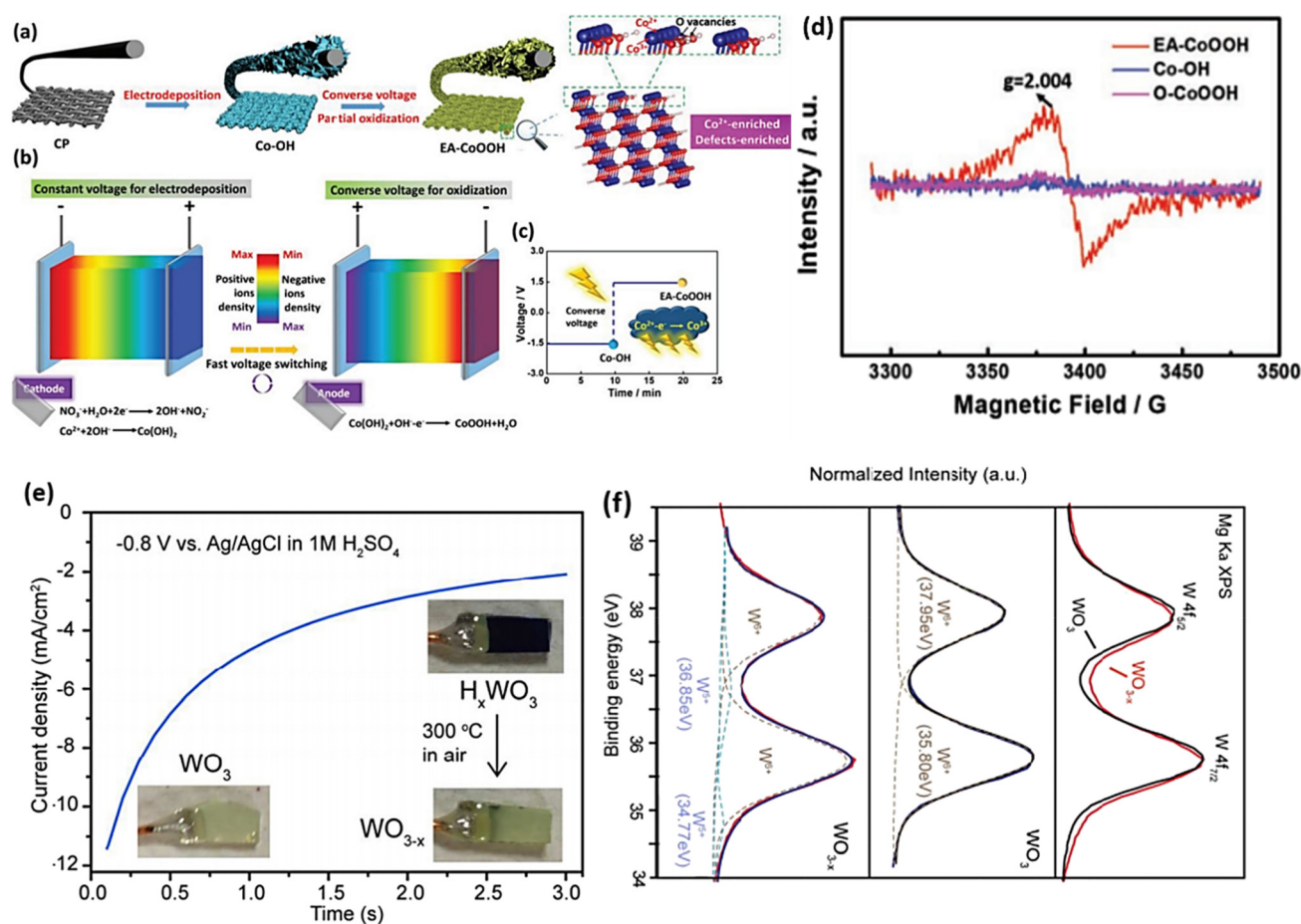


Fig. 12 (a) The molecular structure of EA-CoOOH exhibiting Co^{2+} and defect-enriched characteristics is shown schematically, and its synthesis through the converse voltage approach is also described. (b) Schematic representation of the process, showing a constant voltage used for electrodeposition and a reverse voltage used for oxidation. (c) Electrodeposition voltage and time employed schematic and reverse voltage process stages. (d) Spectra obtained by EPR from the as-prepared materials. Reproduced from ref. 154 with permission from Wiley, copyright 2019. (e) After being exposed to $1 \text{ M H}_2\text{SO}_4$ solution at $-0.8 \text{ V vs. Ag/AgCl}$ for 3 s , the cathodic current vs. time curve of the WO_3 film decreased. Inset: the electrochemical reduction of a light yellow WO_3 film results in a blue H_xWO_3 film, which is then re-oxidized into WO_{3-x} when exposed to air. (f) Upper: WO_3 and WO_{3-x} XPS W 4f spectra after normalization. The synthetic peaks in the XPS W 4f spectrum of WO_3 that correspond to the W 4f_{5/2} and W 4f_{7/2} signal of W^{6+} are shown in the middle of the figure. The experimental data and the total of the synthetic peaks are shown by the black and blue curve. Synthetic peaks may be seen in the XPS W 4f spectrum of WO_{3-x} at the bottom. The red line represents the experimental data, which have been decomposed into two sets of peaks representing W^{6+} and W^{5+} (the dashed lines). The blue line represents a cumulative peak de-convolution. Reproduced from ref. 155 with permission from RSC, copyright 2016.

forward electrochemical reduction technique to produce a range of metal oxides integrated with OVs, namely WO_3 , TiO_2 , ZnO and BiVO_4 .¹⁵⁵ In this study, we use WO_3 as a specific example to demonstrate the induction of OVs using the technique employed. The metal oxides treated electrochemically showed enhanced photoactivity compared with their pristine states. This improvement can be attributed to the creation of oxygen vacancies. The identification of these oxygen vacancies was confirmed by analyzing the XPS data, which revealed a decrease in the valence state of W in OV- WO_3 (Fig. 12f).

4.6 Elemental doping

Doping with appropriate elements is a widely employed and strongly favored method for introducing oxygen vacancies into metal oxides. Extensive research has demonstrated that the presence of OVs varies considerably depending on the doping of diverse metal elements.^{156–160} Doping elements in MOs can provide a wide range of options when considering dopants with

similar ionic sizes and high solubility characteristics. Using a plasma technique, Huang and colleagues.⁵³ successfully created Mo-substituted Co_3O_4 nanoneedles on carbon cloth ($\text{Mo-Co}_3\text{O}_4@\text{CC}$), as depicted in Fig. 13a. The addition of Mo resulted in the induction of OVs, which were verified through XPS and EPR analysis. Theoretical investigations demonstrated that the presence of Mo with varying oxidation states effectively controlled the $\text{Co}^{3+}/\text{Co}^{2+}$ atomic ratio and increased the abundance of OVs. As a result, this caused a reallocation of charges and the modulation of the d-band center of Co_3O_4 , as depicted in Fig. 13b. Jiang *et al.*¹⁶¹ prepared CuO doped with Sn through hydrothermal treatment. The incorporation of Sn led to the generation of OVs, which were confirmed through XPS and EPR analysis. Theoretical investigations indicate that the energy barrier for CO adsorption dimerization is reduced by Sn doping, and it effectively stabilizes the $^*\text{CO}$ and $^*\text{OCCO}$ species (Fig. 13d).

Moreover, it was observed that Sn alone is insufficient to achieve the desired outcomes. However, the combined effects

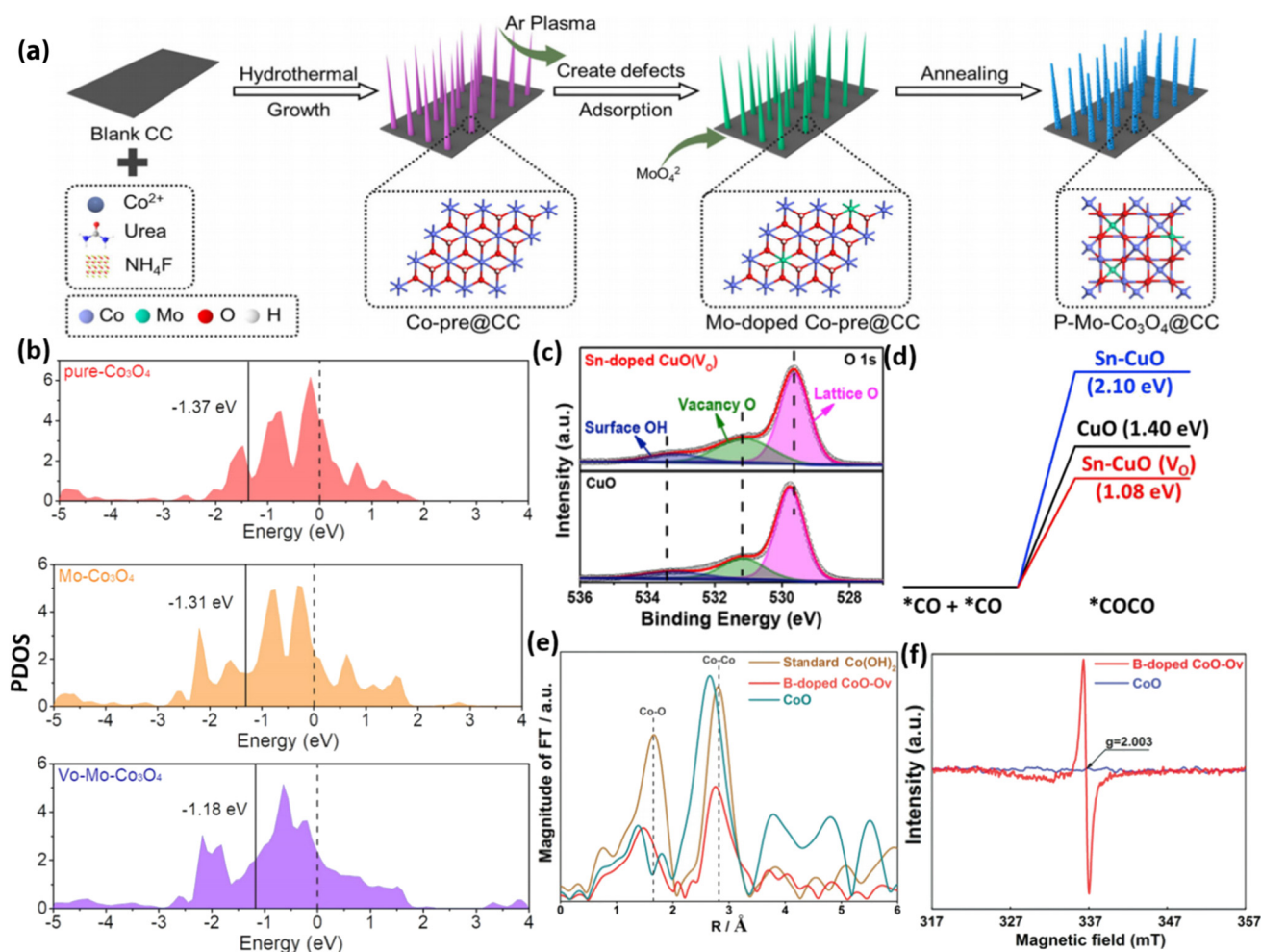


Fig. 13 (a) The figure provides a schematic depiction of the synthesis process for P-Mo- $\text{Co}_3\text{O}_4@\text{CC}$. (b) PDOS of pure- Co_3O_4 , Mo- Co_3O_4 , and V_0 -Mo- Co_3O_4 . Reproduced from ref. 53. (c) XPS O 1s spectra of CuO and CuO that have been doped with Sn (V_0). (d) Diagram illustrating the amount of energy required for CO dimerization ($^*\text{CO} + ^*\text{CO} \rightarrow ^*\text{OCCO}$) on CuO (black), Sn-CuO (blue), and Sn-CuO(V_0) (red). Reproduced with permission.¹⁶¹ (e) The spectra were obtained using the Fourier transform at the Co K-edge for B-doped CoO-Ov, CoO, and conventional $\text{Co}(\text{OH})_2$. (f) Spectra of EPR for B-doped CoO-OV and CoO. Reproduced from ref. 162 with permission from Elsevier, copyright 2021.

of Sn doping and OV's are the key contributors to enhanced catalytic activity. In the investigation by Zhang *et al.*¹⁶² it was reported that the incorporation of non-metal elements can trigger the formation of OV's in the engineered material, as depicted in Fig. 13c. This was demonstrated by synthesizing CoO nanowires containing OV's by adding B using a straightforward pyrolysis technique. The evidence from EPR and XAS analysis supports the notion that the OV's in CoO primarily stem from the perturbation of the local structure induced by B doping (Fig. 13e). In summary, extensive investigations have demonstrated that metal and nonmetal dopants can generate OV's in metal oxides, leading to improved conductivity and rapid ion and electron transport. Nevertheless, the precise control of dopant concentration and spatial distribution within nanostructures of MOs has remained a persistent challenge.

Based on recent literature, the synthesis methods for creating OV's in metal oxide catalysts, along with the corresponding techniques to detect OV's, are summarized in Table 1. These approaches are widely used for introducing vacancies in metal oxides.

5. Recent progress in OV-based electrocatalysts in electrochemical NO₃⁻ reduction to NH₃

Modifying the electronic structure is crucial for optimizing the electrocatalytic activity, and one way to achieve this is through vacancy engineering. By introducing OV's, the electronic arrangement of the host materials can be modified, leading to local rearrangements of spin/charge density and facilitating of the adsorption of intermediates.¹⁷⁰ It is believed that the presence of OV's in TiO₂ can enhance the bonding between Ti³⁺ and oxygen, improving its ability to reduce the oxygen.¹⁷¹ Based on this reasoning, it seems plausible that metal oxides containing OV's could effectively capture and electrochemically reduce nitrate. Nevertheless, there have been few reports on the investigation of OV-rich oxides as prospective electrocatalysts for ammonium synthesis through nitrate electroreduction. Additionally, as the number of OV's in a nanomaterial increases, so does its electrochemical performance. Recognizing the significance of OV's in metal oxides, Jia *et al.*¹⁰⁵ investigated the impact of OV's on the adsorption energy of NO₃⁻ on the TiO₂(101) surface by varying the number of OV's from zero to one and two in TiO_{2-x}. The OV's were formed by subjecting the TiO₂ to a heating process at a rate of 5 °C per minute until it reached a temperature of 700 °C. It was then maintained at 700 °C for 4 hours under a hydrogen atmosphere, followed by a cooling phase (Fig. 14a). XPS and EPR investigations, depicted in Fig. 14b and c, provided evidence substantiating the formation of OV's within the specified material. The electrochemical performance results revealed a notable decline in adsorption energy as the concentration of OV's increased. Specifically, the adsorption energy

decreased from -0.71 eV to -1.44 eV and -1.54 eV, respectively (Fig. 14d). The experimental findings revealed that TiO_{2-x} exhibited a two-fold increase in the yield rate, in addition to a high faradaic efficiency and ammonium selectivity for the electrochemical synthesis of ammonia, with respective values of 0.045 mmol h⁻¹ mg⁻¹, 85.0%, and 87.1% when operated at -1.6 V vs. SCE. This performance significantly surpassed pristine TiO₂ under identical conditions, which recorded 0.024 mmol h⁻¹ mg⁻¹, 66.3%, and 66.9% (Fig. 14e and f). This was achieved by eliminating bridge O, which produced active sites on the top surface of TiO₂(101). The NO₃⁻ ions were prone to accumulate and be captured at these active sites, where their O atoms filled the vacancies while the adjacent unsaturated Ti³⁺ sites trapped another O atom. The presence of numerous OV's in TiO₂ nanotubes caused a shift of the Fermi energy (*E_f*) towards the CBM (conduction band minimum) by occupying the excess 3d electrons of Ti, as reported by the authors. This resulted in the emergence of metallic properties and increased the conductivity in the TiO_{2-x}. It is logical to assume that the engineering of OV's could enhance the conducting property of electrocatalysts for NO₃RR and the electron/proton transfer steps.

In line with these findings, Daiyan *et al.*⁴⁷ noted a comparable tendency where the introduction of additional OV's (three OV's) in CuO lowered the adsorption energy, which in turn facilitated a noteworthy adsorption of NO₃⁻. The introduction of OV's aimed to expose more catalytic sites that can be utilized during the electrocatalytic process. The adsorption energy of NO₃⁻ on CuO(111) increased from -0.93 eV to -0.5 eV with the addition of one OV. Interestingly, as the number of OV's increased, the adsorption energy significantly decreased to -1.84 eV (two OV's) and -2.08 eV (three OV's), as shown in Fig. 14i. These results suggested that an "adequate amount" of OV's within CuO_x is energetically advantageous for NO₃⁻ adsorption, thereby impeding the adsorption of other competing anions on the catalyst surfaces. According to the authors, the defects formed during the process promoted the most energetically favorable path for ammonia production, wherein the crucial step involved the adsorption of nitrate ions with the release of -1.87 eV (CuO with two OV's) and -1.5 eV (Cu₂O), at -0.6 V vs. RHE. Furthermore, it was observed that introducing OV's beyond 1 raises the free energy of H*, which promotes the NO₃⁻ RR while making the HER more challenging (Fig. 14j). The oxygen-rich vacancy CuO_x that was prepared with 5 min plasma treatment (pCuO-5) demonstrated exceptional performance, yielding 292 μmol cm⁻² h⁻¹ of NH₄⁺ (-0.6 V vs. RHE) and FE of 89% at -0.5 V (Fig. 14h). Based on the AES, XPS, and HRTEM data, it was inferred that an excessive amount of OV's on the CuO_x surface led to a decrease in electron density, reduction in surface crystallinity, and alteration in the surface chemical state.

Combining and forming OV's within a dual-cation framework is a promising approach to improve the electrochemical capabilities of the catalyst, resulting in a higher efficiency in converting NO₃⁻ to NH₃. Prior studies have demonstrated that TiO₂ containing vacant oxygen sites exhibits an exceptional

Table 1 Summary of commonly used approaches to construct OV in metal oxides

Synthesis method	Catalysts	Detection techniques	Description of methods	Ref.
Calcination	(TiO _{2-x})	XPS, EPR	20 minutes of H ₂ gas purging of TiO ₂ . Heating at a rate of 5 °C min ⁻¹ to 700 °C, then holding at that temperature under a H ₂ atmosphere for 4 hours.	105
Plasma treatment	CuO	HAADF, Raman, XAS, EPR	Flame spray pyrolysis (FSP) was used to atomize a copper precursor solution using 5 mL min ⁻¹ of oxygen. A 30 mL min ⁻¹ He flow was used to introduce the resulting product into a reaction cell, where it was subjected to a plasma treatment for 5 and 10 minutes.	47
Electrospinning, calcination	Fe ₂ TiO ₅	Raman, XPS, EPR,	To a 1.2 g PVP solution in 5 mL of DMF and 5 mL of ethanol, 1.212 g of Fe(NO ₃) ₃ ·9H ₂ O, and 0.45 mL of butyl titanate were added and stirred for 24 h. The solution was then electrospun (20 kV). After electrospinning, the materials were heat-treated at 250 °C for 1 h and calcined at 650 °C for 3 h.	103
Calcination	a-RuO ₂	XPS, XAS, Raman	20.0 mg ruthenium acetylacetonate (Ru(acac) ₃) and 37.5 mg potassium bromide were dissolved in a 15.0 mL ethanol and distilled water mixed solution. A piece of carbon paper treated at 60 °C for 24 h using water, concentrated nitric acid, and concentrated sulfuric acid was immersed in the abovementioned mixed solution. The solution was dried at 50 °C until the liquid evaporated. Finally, the carbon paper with the dark red precipitates on the surface was heated in a tube furnace at 260 °C for 30 min with a heating rate of 5 °C min ⁻¹ under air.	163
Ar plasma	Cu ₂ O	XPS, XAS, EPR	Treatment times for the pure Cu ₂ O ranged from 20 to 60 minutes in Ar plasma. The plasma treatments were conducted in a 20 Pa-pressured vacuum chamber, with a radio frequency generator power of 200 W.	164
Elemental doping	Fe-TiO ₂	XPS, EPR, Raman	0.1 g of the prepared TiO ₂ was added into 10 mL of CH ₃ CN solution containing 30 mg of Fe(acac) ₃ . The obtained powders after filtration were dried at 70 °C in a vacuum for 6 h and calcined at 350 °C for 2 h under a reducing atmosphere (5 vol% hydrogen and 95 vol% argon) to obtain Fe-TiO ₂ electrocatalysts.	165
Calcination	LaCoO ₃ , LaMnO ₃ , LaCrO ₃ , LaFeO ₃	XPS, EPR	La(NO ₃) ₃ ·H ₂ O (2 mmol) and Co(NO ₃) ₂ ·6H ₂ O (2 mmol) were dissolved in 70 mL water. Then, C ₆ H ₈ O ₇ (6 mmol) and C ₁₀ H ₁₆ N ₂ O ₈ (4 mmol) were added as complexing agents. The pH of the mixed solution was adjusted to alkaline by adding NH ₃ ·H ₂ O dropwise. Afterward, the solution was heated at 90 °C under stirring and slowly evaporated to obtain the gel. The resulting gel was roasted at 250 °C for 5 h to form a solid precursor and then calcined at 800 °C for 10 h in air. The precipitates were collected and ground to obtain a LaCoO ₃ perovskite. The same procedure was used for the rest of the catalyst.	84
Nano-crystallization	TiO ₂	XRD, XPS, UV-Vis DRS	Ti(SO ₄) ₂ was reacted with ammonia water in an ice-water bath for 2 hours, and then TiO ₂ was obtained after centrifuging, washing, and drying the solution at 80 °C. The produced TiO ₂ was subjected to an ultrasonic treatment at 80 °C for varying times (0.5 h, 1 h, 2 h, 4 h, and 8 h) with an output power density of 1500 W/100 mL.	166
Nano-crystallization	Bi ₂ O ₃	HAADF STEM, XPS, ESR, PL	Hydrothermal treatment at 453 K for 12 hours was applied to a mixture of 800 mg bismuth, 60 mg propylamine, and 30 mL benzyl alcohol. Following centrifugation, 400 mg of the precipitates were redissolved in 100 mL of a 1 : 1 solution of isopropanol and water.	167
Elemental doping	MoO ₃ /Ce	XPS, EPR, PAS	In a cold water bath, 5 × 10 ³ molar Mo powder was added to 10 mL of H ₂ O ₂ . While still stirring, 50 mL of deionized water and 10 mL of 100% ethanol were added to the aforementioned mixture. Then, Ce(NO ₃) ₃ ·6H ₂ O was added, and the mixture was agitated for a further 2 hours. The combined solution was heated to 140 °C for 18 hours to react. Collecting the dark blue goods, we cleaned them in deionized water and pure ethanol. The samples were then dried in an oven at 60 degrees celsius for 12 hours.	109
Elemental doping	Fe-TiO ₂	XPS, EPR, XAS	600 mg of PVP dissolved in 5 mL of ethanol was stirred for 2 h at 60 °C. 1 mL of acetic acid was added and stirred for 30 minutes. Then tetrabutyl titanate containing different mole fractions of acetylacetonate iron was added and stirred for 1 h. The final mixture was subjected to electrospinning under a 20 kV voltage at the rate of 2 mL h ⁻¹ . The obtained membrane was annealed at 550 °C for 2 h and held at 800 °C for 1 h with a heating rate of 5 °C min ⁻¹ in air.	168

Table 1 (Contd.)

Synthesis method	Catalysts	Detection techniques	Description of methods	Ref.
Plasma treatment	InOOH	XPS, EPR, HAADF-STEM	270 mg of $\text{In}(\text{NO}_3)_3 \cdot 4\text{H}_2\text{O}$ and 2 g of urea in 60 mL of ethanol were stirred. Then, 65 mg of CB (commercial XC-72R) was added, subjected to ultrasound treatment for 30 min, and heated at 90 °C for 12 h. The resulting sample was filtered, washed and dried at 60 °C for 12 h under a vacuum. The as-prepared InOOH was subjected to Ar plasma for 2 min to induce OV in InOOH.	169
Self-assembly solvothermal method	$\text{Bi}_{24}\text{O}_{31}\text{Br}_{10}$	XPS, EPR, STEM and XAFS	0.243 g bismuth nitrate pentahydrate, 0.27 g mannitol and 0.2 g polyvinyl pyrrolidone (average mol wt 40 000) are added into 15 mL water and ultrasonicated. Then, the 3 mL KBr solution (0.5 mmol KBr) is injected under stirring. The pH is adjusted to 7.5 by 2 M sodium hydroxide solution and stirred for 0.5 h. After solvothermal treatment for 24 h under 160 °C, the sample is collected, washed with hot ethanol and water, and dried.	91

Table 2 The advantages and significance of the NO_3RR compared with other electrochemical NH_3 synthesis routes^{238,242}

N_2 electrochemical reduction	NO electrochemical reduction	NO_3^- electrochemical reduction
<ul style="list-style-type: none"> The solubility challenge of the conventionally used inert N_2 has consequences for the generation of ammonia (NH_3) in aqueous environments. The considerable energy needed to break the bonds in N_2 makes it economically unfeasible for the electrochemical production of NH_3. Most catalysts investigated exhibit a low yield rate and low faradaic efficiency (FE). Thus, while utilizing N_2 gas as the nitrogen source for electrochemical NH_3 synthesis holds promise, it still requires significant progress to achieve substantial yields suitable for practical applications. The reaction potential closely aligns with that of the hydrogen evolution reaction (HER). As a result, the electrochemical reduction of N_2 is significantly hampered by the HER. 	<ul style="list-style-type: none"> The challenge of solubility in aqueous solutions directly impacts ammonia (NH_3) production. Environmental samples typically contain a low concentration of NO, necessitating an additional energy-intensive step to concentrate it for the electrochemical reaction. Non-precious metal-based catalysts exhibit a drawback in the form of low yield rates and faradaic efficiency (FE). Nevertheless, achieving the practical implementation of cost-effective and long-lasting catalysts remains a distant aspiration. Most of the investigated catalysts produce side products alongside the reduction of NO to NH_3. Further advancements in catalyst design are necessary since the reduction of NO to NH_3 is still in an early developmental stage. 	<ul style="list-style-type: none"> Nitrate ions (NO_3^-) have gained prominence as a significant nitrogen source in contrast to the conventionally inert N_2 for the electrochemical generation of NH_3, contributing to their widespread prevalence as water pollutants across the globe. The low bond dissociation energy in NO_3^- renders this molecule an appealing candidate for NH_3 synthesis. A broad range of electrocatalysts have shown noteworthy improvements in both faradaic efficiency (FE) and yield rates. There is a significant disparity between the reaction potential of NO_3^- (0.69 V) and that of the hydrogen evolution reaction (HER). Therefore, the reduction of NO_3^- to NH_3 successfully circumvents the impediments posed by the hydrogen evolution reaction (HER). Lastly, the presence of NO_3^- in water samples poses a threat to human health, and the transformation of this waste into a valuable product holds significant importance, serving both environmental remediation and the production of versatile chemicals.

electrochemical performance.^{106,172} Iron (Fe), a key component in the Haber–Bosch process, has been identified as a potential catalyst for nitrate reduction. In a recent study, Du *et al.*¹⁰³ were inspired by the double-cation model and proposed the use of defective pseudobrookite Fe_2TiO_5 nanofiber (FTO-E) as a new electrocatalyst to reduce nitrate to ammonia under ambient conditions. This electrocatalyst was prepared using the electrospinning technique and contains abundant oxygen vacancies (Fig. 15a and i). Oxygen vacancies in the prepared material were confirmed through spectral analyses using the XPS and EPR techniques (Fig. 15j and k). The higher intensity of the ESR signal suggests a greater number of oxygen vacancies (V_{O}) formed in FTO-E than in FTO-H (FTO prepared

by the hydrothermal method). This observation is likely due to the tendency of high-reducibility Fe^{3+} ions to replace Ti^{4+} ions, thereby inducing the formation of oxygen vacancies. The density of states calculations have revealed that introducing OV into FTO significantly enhances its conductivity, with electronic contributions from O and Fe atoms evident based on the band contribution calculations (Fig. 15l and m). Moreover, the d-band center (ϵ_{d}) is observed to shift to a higher level upon generating a V_{O} , which contributes to the catalyst's higher catalytic activity. The thermodynamic study indicates that the adsorption of the NO_3^- group on pristine FTO results in a free energy of 0.09 eV, significantly reduced to -0.28 eV upon adding V_{O} (Fig. 15n). In contrast, the adsorption energies

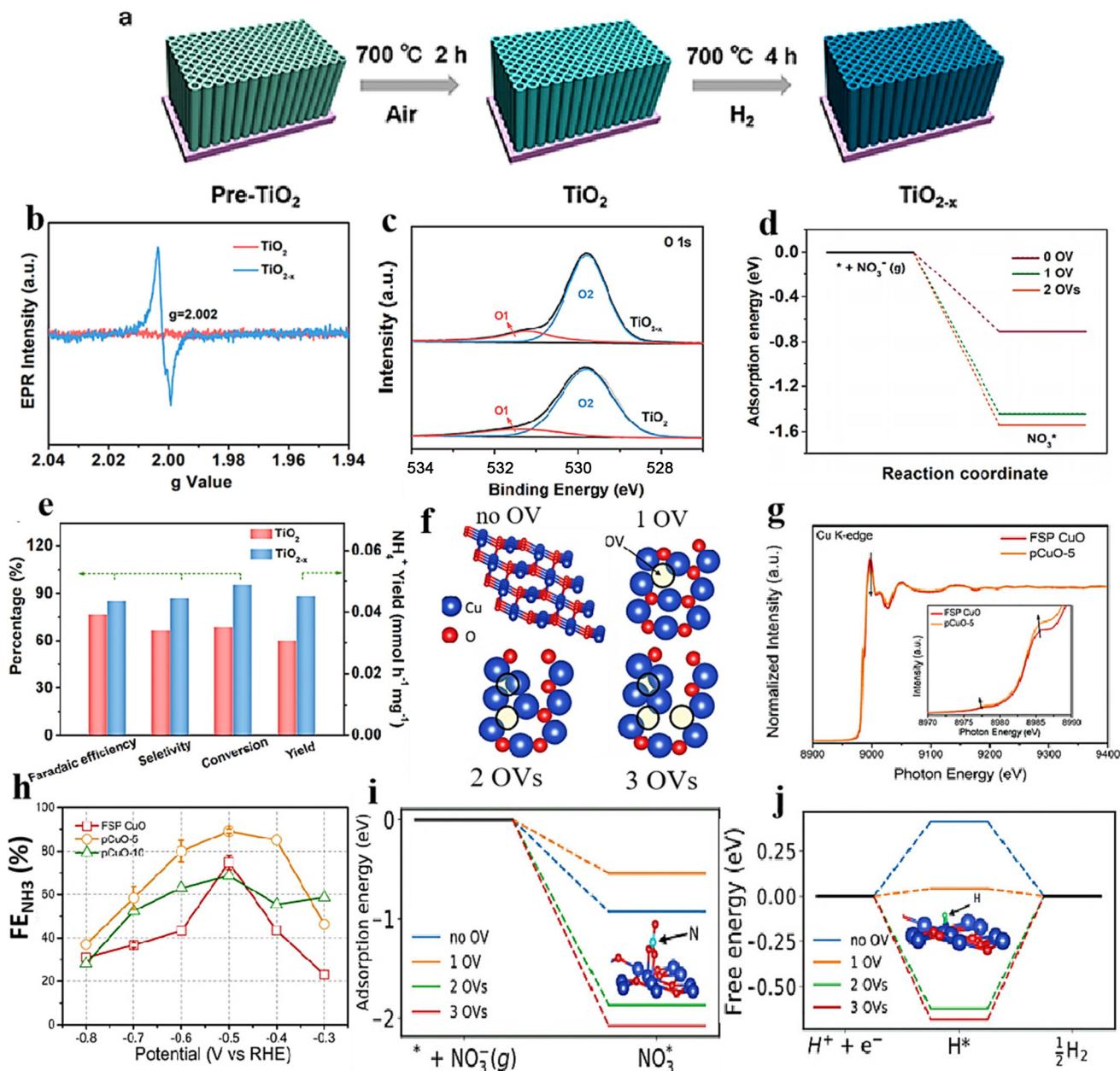


Fig. 14 (a) TiO_{2-x} synthesis diagram. (b) EPR spectral analysis. (c) TiO_2 and TiO_{2-x} XPS spectra. (d) Energy required for NO_3^- adsorption on $\text{TiO}_2(101)$ surfaces with 0 OVs, 1 OVs, and 2 OVs. (e) TiO_{2-x} and TiO_2 were compared with respect to their NH_4^+ FE, selectivity, yield, and NO_3^- conversion rate. Reproduced from ref. 105 with permission from the American Chemical Society, copyright 2020. (f) Top view of the relaxed structures of the $\text{CuO}(111)$ surface with 1, 2, and 3 OVs, with the missing oxygen atoms indicated by the circles in the pristine $\text{CuO}(111)$ slab model used in DFT calculations. (g) XANES spectra obtained experimentally near the Cu K edge, as well as enlarged curves (insets) of FSP CuO and pCuO-5. (h) The dependency of the FENH_3 concentration on the applied potential for FSP CuO, pCuO-5, and pCuO-10 in 0.05 M KNO_3 and 0.05 M H_2SO_4 . (i) NO_3^- adsorption energies on $\text{CuO}(111)$ were calculated for 0 OVs, 1 OVs, and 3 OVs. (j) The corresponding HER free energy diagram. Reproduced from ref. 47 with permission from RSC, copyright 2021.

of NO_3^- on pristine TiO_2 and $\text{TiO}_2\text{-VO}$ are much higher, at 1.52 eV and 0.45 eV, respectively, compared with the 0.28 eV value observed for FTO- V_O . The electrochemical efficiency of the FTO-E catalyst was studied and it was observed that at -1.0 V vs. RHE, it achieved a high FE of 87.6% and a large NH_3 yield of $13.3 \text{ mg h}^{-1} \text{ mg}_{\text{cat}}^{-1}$. These values were further enhanced to

96.06% and $1.36 \text{ mmol h}^{-1} \text{ mg}_{\text{cat}}^{-1}$ at 0.9 V vs. RHE (Fig. 15o). The catalytic importance of iron (Fe) has also been evidenced across multiple catalysts employed in the electrochemical process of reducing nitrate to ammonia. For example, the introduction of Fe doping into V_2O_5 (resulting in $\text{Fe-V}_2\text{O}_5$) has been documented to generate Lewis acid sites on the catalyst's

surface, leading to an increased electrochemical conversion of nitrate to ammonia.¹⁷³ Similarly, the incorporation of Fe within FeB₂-based MBenes has been observed to greatly elevate the catalytic capabilities of the tandem MBene catalyst.^{174,175}

The degree of structural disorder is crucial for a catalyst's catalytic performance, yet its impact on NO₃⁻ reduction is often overlooked. It is crucial to investigate how the level of disorder affects the electrocatalytic NO₃⁻ reduction performance. To tackle this issue, Wang *et al.*¹⁶³ created a-RuO₂, which comprises amorphous RuO₂ nanosheets grown on a carbon

paper substrate, using a straightforward molten-salt preparation method. To facilitate a comparison with a-RuO₂, the researchers prepared two variations of RuO₂ with different degrees of crystallinity, referred to as lc-Ru₂O (low crystallinity) and hc-RuO₂ (high crystallinity). Structural disorder in the prepared samples was identified through an investigation using EXAFS (extended X-ray absorption fine structure). The values obtained from the EXAFS spectral study confirmed the formation of structural disorder in the samples (Fig. 16f). The XPS study successfully identified the presence of OV, and it

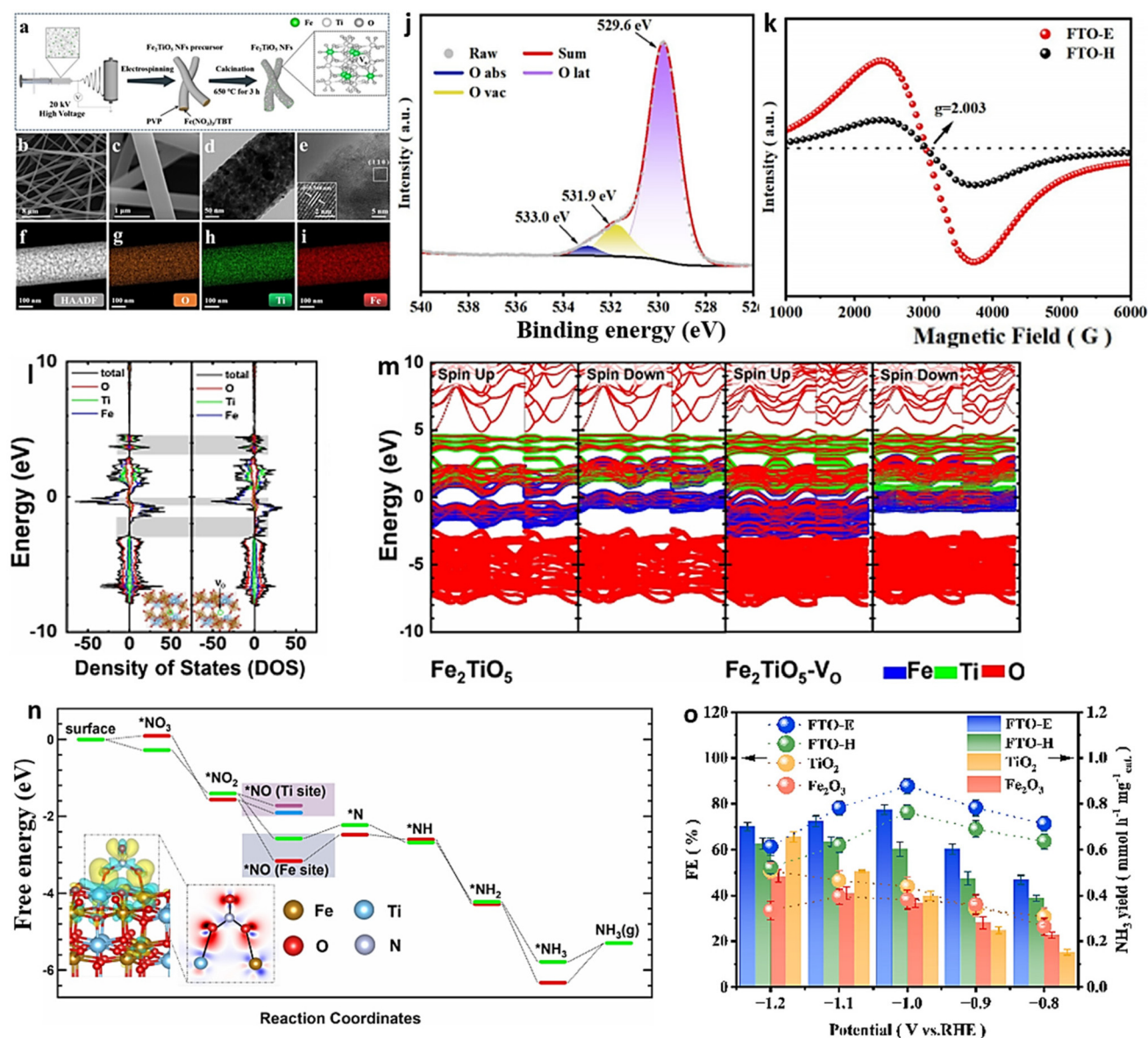


Fig. 15 (a) Illustration of the schematic for the manufacturing process of the FTO-E electrocatalyst. (b) and (c) Images of FTO-E taken at different SEM magnifications. (d) TEM analysis of FTO-E. (e) HR-TEM photo of FTO-E. (f) HAADF STEM image and EDX mapping of the O (g), Ti (h) and Fe (i) elements in FTO-E. (j) XPS spectra of O in FTO-E. (k) EPR spectra of FTO-E and FTO-H. (l) Calculated density of states (DOS) of Fe₂TiO₅ and Fe₂TiO₅-VO. (m) The band structures of both Fe₂TiO₅ and Fe₂TiO₅-VO were calculated. The contributions to the band made by iron, titanium, and oxygen are denoted by the colors blue, green, and red, respectively. (n) Fe₂TiO₅ and Fe₂TiO₅-VO free energies. The bottom left shows the NO₃⁻ charge density differential on Fe₂TiO₅-VO. Yellow and blue indicate charge surplus and deficiency. (o) FEs and NH₃ yield of various samples at each given potential. Reproduced from ref. 103 with permission from Wiley, copyright 2022.

was observed that among the three samples, a-RuO₂ exhibited the largest peak area for O1. This observation indicates that a-RuO₂ possesses a significantly higher number of oxygen vacancies than the other two samples (Fig. 16d). Remarkably, a-RuO₂ demonstrates exceptional performance in NO₃⁻ reduction, surpassing its crystalline counterparts lc-RuO₂ (FE: 55.27%, selectivity: 77.76% and YR 0.0222 mmol h⁻¹ cm⁻²) and hc-RuO₂ (FE: 7.03%, selectivity: 19.22%, YR 0.0013 mmol h⁻¹ cm⁻²) by exhibiting a high FE of 97.46%, a significant selectivity of 96.42%, and a YR of 0.1158 mmol h⁻¹ cm⁻² at -0.35 V vs. RHE. Through both experimental and theoretical calculations, it can be deduced that a-RuO₂'s disordered atomic arrangement provides an abundance of oxygen vacancies. The remarkable selectivity and faradaic efficiency of this specially designed disordered structure can be attributed to the following factors, which have been determined through experimental and theoretical observations: 1: The disordered framework of a-RuO₂, which is rich in oxygen vacancies, is found to influence the hydrogen affinity and d-band center, thereby reducing the energy required for the potential-determining step (NH₂* → NH₃*). 2: The vacancies also cause the d-band electrons to distribute closer to the Fermi level (PDOS), resulting in an improved adsorption of critical intermediates and a lower reaction energy for the potential-determining step (Fig. 16e). 3: Unlike c-RuO₂ (0.33 eV), a-RuO₂ needs a higher energy of 0.73 eV to generate the by-product H₂ (Fig. 16g), which means it suppresses H₂ production and enhances selectivity for a maximum product yield (Fig. 16h).

CeO₂, a significant rare earth metal oxide, displays impressive electronic and ionic conductivity. This is due to its ability to transition between the oxidation states of Ce³⁺ and Ce⁴⁺ flexibly. Moreover, the Ce³⁺ groups that are exposed can serve as potential active sites, effectively absorbing catalytic reaction intermediates.¹⁷⁶ Combining CeO₂ with OV and highly conductive carbon creates an appealing catalyst that can potentially enhance the electrocatalytic performance of NO₃⁻ reduction. This approach inspired Li *et al.*¹⁷⁷ to integrate CeO₂ nanoparticles with V_O decorated N-doped carbon nanorods grown on graphite paper (CeO_{2-x}@NC/GP) to transform NO₃⁻ into NH₃. The identification of OVs was accomplished through XPS and EPR investigations. A noticeable peak at 530.8 eV in the oxygen spectral analysis and a significant signal at *g* = 2 in the EPR spectrum confirmed the OV formation (Fig. 16i and j). The CeO_{2-x}@NC/GP catalyst yielded a significant amount of NH₃, with a value of 712.75 μmol·h⁻¹·cm⁻² at -0.8 V vs. RHE, and demonstrated an impressive FE of 92.93% at -0.5 V vs. RHE in a solution containing 0.1 M NaOH and 0.1 M NO₃⁻ (Fig. 16k and l). Theoretical calculations indicate that CeO₂(111) with oxygen vacancies (-1.47 eV) is much more susceptible to adsorbing NO₃⁻ than pristine CeO₂(111) (1.96 eV), leading to efficient reduction to NH₃ (Fig. 16m). During the NO₃⁻ adsorption process on CeO₂(111) containing V_O, one O atom takes up the V_O site, another O atom binds with the Ce atom, while the remaining O atom is exposed to the surrounding environment. Therefore, CeO₂(111) with oxygen vacancies

can better adsorb and activate NO₃⁻ in the electrochemical conversion process.

Previous research has indicated that the morphology of nanomaterials has a significant impact on their electroactivity. The electrocatalytic performance can be significantly enhanced, in particular, by using hollow nanocatalysts because they expose more active sites and optimize atom utilization.^{178,179} Wang *et al.*⁴⁶ recognized the significance of vacancies and a hollow architecture in catalysis and developed defective Cu₂O nanocubes, referred to as Cu₂O h-NCs (Fig. 17A and B), using a straightforward reduction method. The examination of O 1s spectra through XPS displayed a distinct peak at 531.2 eV, confirming the formation of OVs in the engineered material (Fig. 17D). A faradaic efficiency (FE) of 92.9% and NH₃ yield of 56.2 mg h⁻¹ mg_{cat}⁻¹ for NH₃ synthesis at 0.85 V (vs. RHE) were both signs of the exceptional performance of the resultant catalyst (Fig. 17E). According to the researchers, the high performance of the catalyst may be owing to its abundant oxygen vacancies, hollow structure, and remarkable adsorption capacity towards NO₃⁻ ions. Similarly, nanosheets with two dimensions (2D) are considered to have potential as electrocatalytic structures due to their effective surface efficiency, which results in more surface atoms being available as active sites.¹⁸⁰ However, the high aspect ratio of 2D structures creates limitations on mass transfer, which makes their NO₃RR kinetic reaction less desirable.^{181,182} A multiscale defect method could be used to combat this problem and boost active sites through oxygen vacancies while enhancing mass transfer on 2D nanosheets. To improve the catalytic and mass transfer capabilities, Zhao *et al.*¹⁸³ implemented a successful electrodeposition and calcination technique (Fig. 17F) to create a multi-scale, defective Co₃O₄/Co material with an interwoven nanosheet structure. This approach introduces atomic defects, specifically OVs on Co₃O₄, which increases the number of low-coordinated sites. Moreover, the nanoscale defects, *i.e.*, nanoholes, create additional channels for easier mass transfer. Regarding the fine spectra of Co₃O₄ O 1s, the appearance of an obvious peak at 531.1 eV, along with a prominent EPR signal at 2.004 g, verifies the presence of OVs in the synthesized samples (Fig. 17G and H).¹⁸⁴ Comparatively, the Co₃O₄/Co-h spectrum exhibits higher intensity than the Co₃O₄/Co-l spectrum, indicating a greater concentration of OVs. This higher concentration is advantageous for generating additional electrochemical sites and sequestering more nitrates. The Co₃O₄/Co catalyst demonstrates exceptional NO₃RR properties in a neutral electrolyte thanks to its porosity, defective nanosheet architecture, and controlled oxygen vacancy. The catalyst can accommodate more nitrate on active sites, leading to an impressive ammonia yield rate of 4.43 mg h⁻¹ cm⁻² and a high faradaic efficiency of 88.7%. Theoretical calculations suggest that the oxygen vacancy enhances nitrate adsorption energy, suppresses the HER, and modifies the rate-limiting step of *NO → *HNO. The energy required for NO₃⁻ adsorption on Co₃O₄ with no vacancies is 0.68 eV, which is higher than that of Co₃O₄-1Ov (-1.44 eV) and Co₃O₄-2Ov (-1.81 eV) (Fig. 17I). This indicates that the presence of

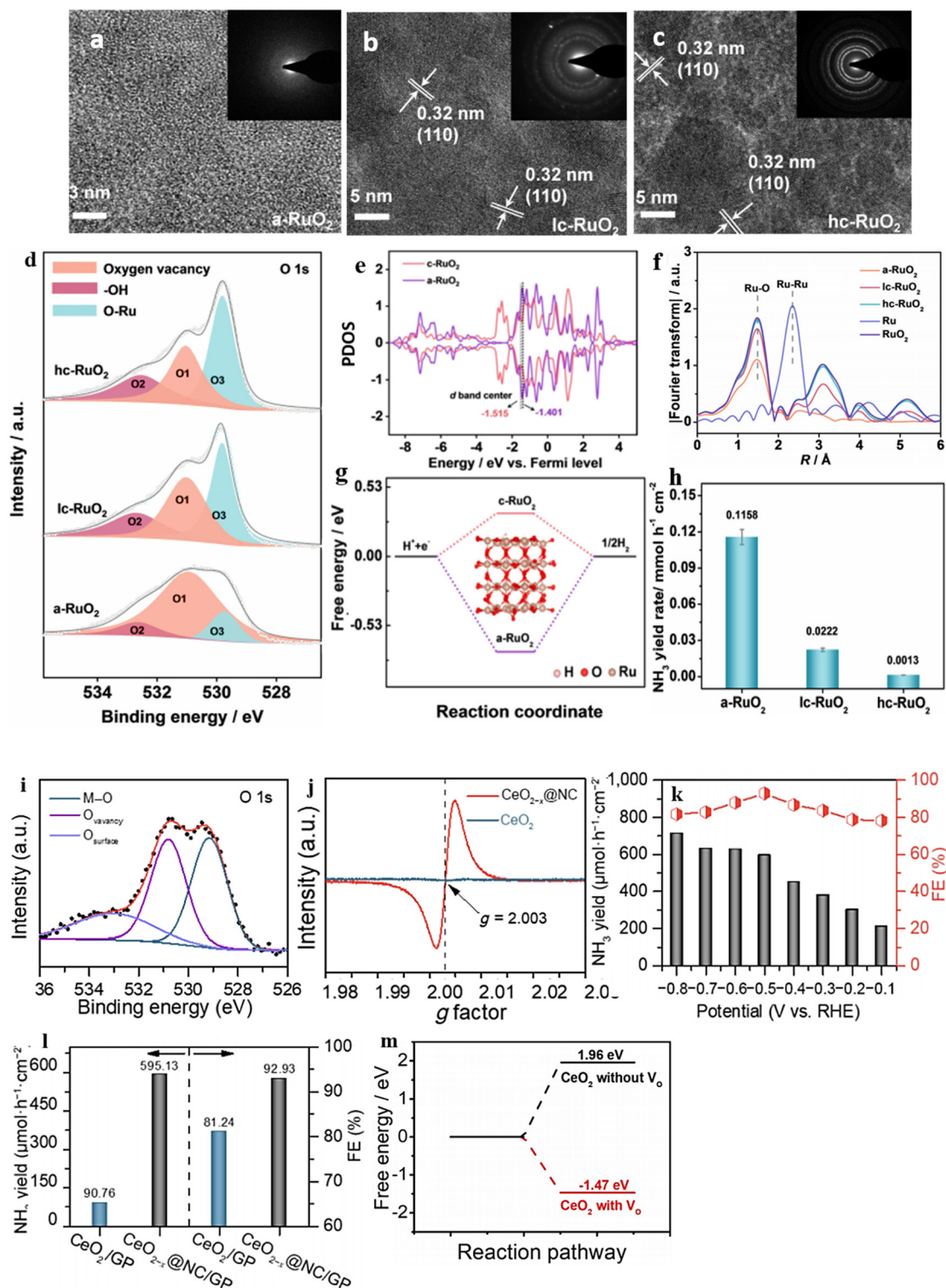


Fig. 16 HRTEM images of (a) a-RuO₂, (b) lc-RuO₂, and (c) hc-RuO₂. The insets in (a)–(c) are the corresponding SAED images. (d) O 1s XPS spectra of a-RuO₂, lc-RuO₂, and hc-RuO₂. (e) PDOS of d-bands for a-RuO₂ and c-RuO₂ and the corresponding d-band centers. (f) k²-Weighted Fourier-transformed EXAFS spectra of Ru K-edge of the as-prepared a-RuO₂, lc-RuO₂, and hc-RuO₂. (g) The reaction energies of H₂ formation over a-RuO₂ and c-RuO₂. (h) The NH₃ yield rate on a-RuO₂ and c-RuO₂. Reproduced from ref. 163 with permission from Wiley, copyright 2023. (i) and (j) XPS spectra of O 1s and EPR spectra of CeO_{2-x}@NC and CeO₂. (k) and (l) NH₃ yield at different potentials on CeO_{2-x}@NC and the NH₃ yield of different materials. (m) Calculated free energy on CeO₂ with and without OV. Reproduced from ref. 177 with permission from Springer Nature, copyright 2022.

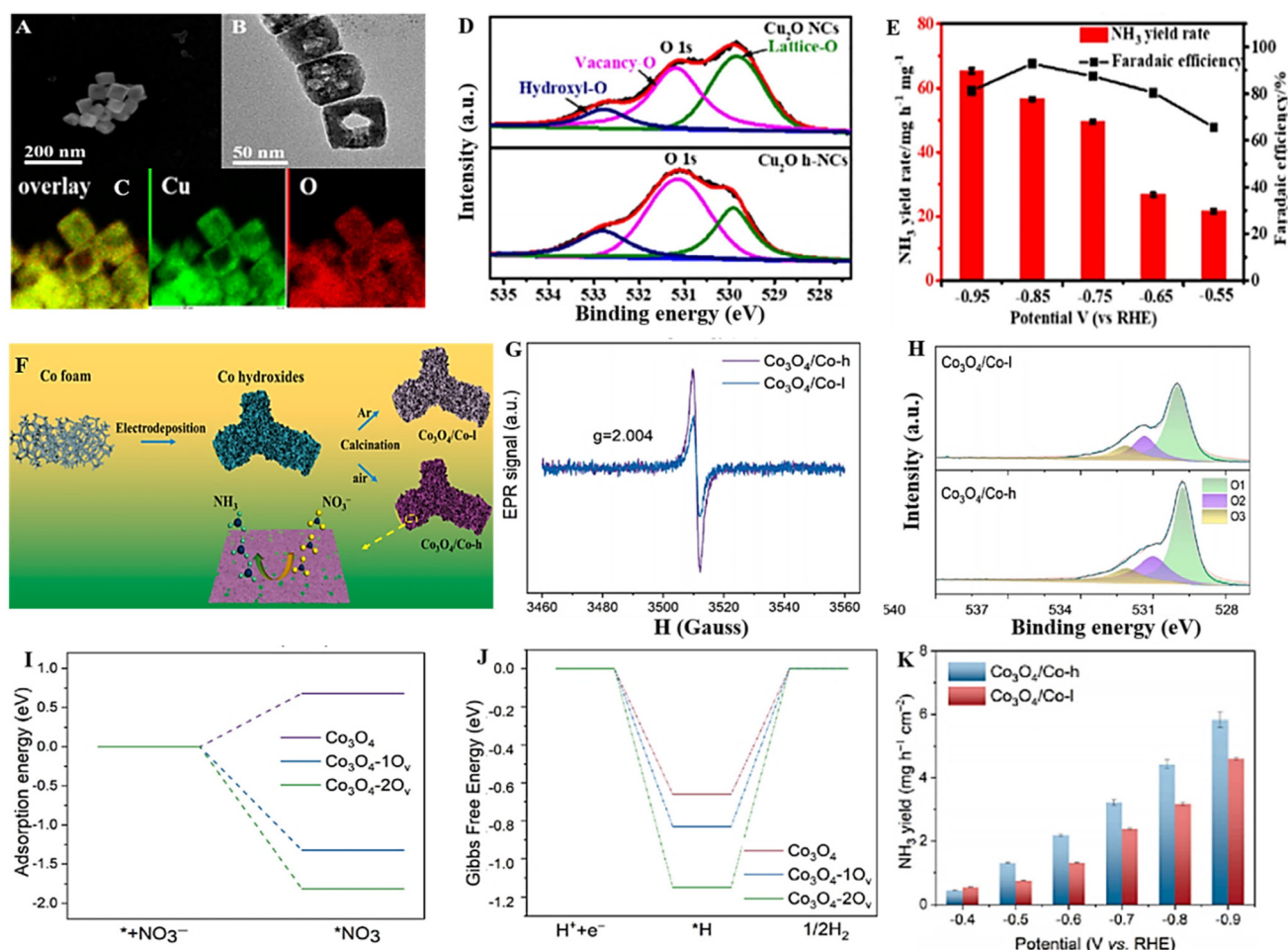


Fig. 17 (A) SEM, (B) TEM, and (C) EDX map images of Cu_2O h-NCs. (D) O 1s XPS spectra and (E) NH_3 yield and the corresponding FE of NO_3^- reduction to NH_3 on Cu_2O h-NCs. Reproduced from ref. 46 with permission from the American Chemical Society, copyright 2022. (F) A graphic photograph of the Co_3O_4 synthesis process. (G) EPR spectra, (H) XPS O 1s spectra. (I) The adsorption energy of NO_3^- on various Co_3O_4 models. (J) Gibbs free energy of H_2 generation. (K) NH_3 yield of Co_3O_4 samples at different potentials. Reproduced from ref. 183 with permission from Elsevier, copyright 2023.

sufficient oxygen vacancy defects on Co_3O_4 promotes energetically favorable NO_3^- adsorption and enhances NO_3RR activity. In terms of the HER (Fig. 17J), the energy barrier required for hydrogen evolution is higher for $\text{Co}_3\text{O}_4\text{-}2\text{O}_\text{v}$ (1.15 eV) compared with $\text{Co}_3\text{O}_4\text{-}1\text{O}_\text{v}$ (0.83 eV) and Co_3O_4 (0.66 eV). This implies that the HER on $\text{Co}_3\text{O}_4\text{-}2\text{O}_\text{v}$ is less feasible than the other two, and the presence of oxygen vacancies acts as an inhibiting factor for the HER. These favorable features help to clarify the reason for the high FE of the $\text{Co}_3\text{O}_4\text{-}2\text{O}_\text{v}$ sample (Fig. 17K).

Gong *et al.* conducted a study using an Ar plasma treatment method to produce Cu_2O with oxygen vacancies. XPS measurements were employed to analyze the oxygen analysis of both untreated and plasma-treated Cu_2O samples (Fig. 18a and b). The amount of OV increased gradually as the plasma treatment time was extended, aligning with the observations in the EPR spectra (Fig. 18c). However, a slight decrease in OV content was observed at a plasma treatment time of

60 minutes, possibly due to numerous surface oxygen species formation. The XAS analysis revealed two peaks at 934.7 and 937.4 eV in the Cu-L edge spectra, signifying the Cu(I) and Cu(II) states. The Cu(II) peak exhibited significantly higher intensity in the Ar-40 sample, indicating a greater abundance of the unoccupied density of states on the Cu sites (Fig. 18d and e). The study revealed that Cu_2O exposed to plasma treatment (40 minutes) exhibited the highest activity in the NO_3RR , yielding an NH_3 selectivity and FE of 85.7% and 89.54%, respectively, at -1.2 V vs. Ag/AgCl (Fig. 18f). According to the results of several DFT calculations, the polarization charge density of copper surrounding an oxygen vacancy ($10.78e^-$) is higher than the polarization charge density of copper in the initial sample ($10.46e^-$) (Fig. 18g). This increased charge density in the vicinity of the Cu sites, combined with an upshifted d-orbital, could enhance electron transfer between the surface and reaction intermediates,^{185–187} resulting in a notable improvement in the NO_3RR . Likewise, Cu_2O with one oxygen

vacancy (Cu_2O with OV) on the (111) surface shows a significant reduction in the adsorption energy of NO_3^- (-2.25 eV) compared with the pristine Cu_2O surface (-0.97 eV). This trend is also observed for other reaction intermediates, which display lower adsorption energies on Cu_2O with OV than on the pristine surface. The enhanced performance of the defective Cu_2O can be attributed to the combination of an increased charge density, upshift of the d-orbital, and reduced adsorption energies of NO_3^- and other reaction intermediates. Cu/ TiO_2 hybrid catalyst was prepared by Zhang and their team,¹⁰⁶ which involved the uniform dispersion of Cu clusters on TiO_2 nanosheets with a high concentration of OVs (Fig. 18h). The XPS and EPR spectral studies in Fig. 18i and j confirmed the presence of an oxygen vacancy in the designed catalyst. According to a DFT study, the incorporation of both OVs and Cu clusters can augment the interstitial states and improve the electroconductivity, which is advantageous for enhancing the reactivity of the NO_3RR (Fig. 18k). Bader analysis demonstrated that the transfer of 1.47 and 1.39 electrons occurred from Cu clusters to TiO_2 and TiO_{2-x} , respectively. Consequently, the Cu/ TiO_2 functioned as a donor-acceptor pair, thereby promoting the absorption/separation of NO_3^- and the desorption of NH_3 . The hybrid catalyst $10\text{Cu}/\text{TiO}_{2-x}$ was able to significantly enhance the performance of ammonia synthesis, yielding a faradaic efficiency of 81.34% and a rate of NH_3 production of 0.1143 mmol h^{-1} mg^{-1} at a voltage of -0.75 V (Fig. 18l).

In a recent study, Wang and colleagues¹⁶⁵ introduced Fe atoms to TiO_2 nanowires, resulting in many OVs and a charge redistribution in the designed material. This, in turn, led to the formation of numerous active sites essential for nitrate reduction while simultaneously inhibiting proton reduction. Furthermore, the positively charged surface of Fe sites played a critical role in preventing proton access, suppressing hydrogen evolution, and promoting the adsorption and activation of nitrate. The electronic structure of FeTiO_2 was examined through DOS analyses (Fig. 19e), revealing that the O 2p state predominantly contributes to the VBM (valence band maximum). In contrast, the Ti 3d state controls the CBM (conduction band minimum). Bader charge investigation indicated that the average Bader charges for $\text{Fe-TiO}_2\text{-V}_{\text{O}1}$, $\text{Fe-TiO}_2\text{-V}_{\text{O}2}$, and $\text{Fe-TiO}_2\text{-V}_{\text{O}3}$ were decreased to 1.85, 1.87, and 1.84, respectively, all of which were lower than that of pristine TiO_2 (1.97) (Fig. 19f). This indicates that introducing Fe atoms led to a charge redistribution in the system. Based on the Gibbs free energy pattern, it can be observed that the $\text{Fe-TiO}_2\text{-V}_{\text{O}3}$ material was the most stable structure with induced defects for both NO_3^- adsorption and subsequent reduction among the prepared materials (Fig. 19g). In addition, $\text{Fe-TiO}_2\text{-V}_{\text{O}3}$ demonstrated a higher energy barrier for competitive H_2 generation (1.44 eV) than pristine TiO_2 (-0.46 eV), indicating a stronger suppression of H_2 production in the Fe-doped system (Fig. 19h and i). This effect can be attributed to the positively charged surface of Fe, which repels protons more effectively. The suppression of H_2 production in Fe-TiO_2 promotes a high faradaic efficiency. As a result, Fe-doped TiO_2 demonstrated enhanced catalytic performance in the NO_3RR . Fe-TiO_2 exhibited a sig-

nificantly improved electrocatalytic performance in nitrate reduction, with an ammonia yield rate of 137.3 mg h^{-1} $\text{mg}_{\text{cat.}}^{-1}$ and a faradaic efficiency of 92.3% at -1.4 V (vs. RHE), as compared with pristine TiO_2 (which had an ammonia yield rate of 28.8 mg h^{-1} $\text{mg}_{\text{cat.}}^{-1}$ and a faradaic efficiency of 54.7%).

ZnCr_2O_4 nanofiber, a zinc-rich spinel, was synthesized by Dong *et al.*¹⁸⁸ and used as a high-performance NO_3RR electrocatalyst for ambient NH_3 synthesis. The electrocatalytic performance was effectively boosted by substituting bivalent Zn ions for trivalent chromium, which modulated the OVs. The catalyst with the highest OVs achieved an optimal NH_3 yield rate of 20.36 mg h^{-1} $\text{mg}_{\text{cat.}}^{-1}$ and an FE of 90.21% at -1.2 V vs. RHE. According to theoretical calculations, ZnCr_2O_4 forms OVs that alter the energy levels of the d-band center (ϵ_d) of Cr and Zn, raising it for Cr and lowering it for Zn. These energy level shifts create primary sites for nitrate adsorption and ammonia desorption. Additionally, the insertion of Zn and V_O results in the creation of more antibonding states.¹⁸⁹ Moreover, the Zn-rich surface of the ZnCr_2O_4 catalyst facilitates the transfer of electrons from the metal active site, resulting in the efficient reduction of NO_3^- to NH_3 .

Due to its cost-effectiveness and eco-friendliness, manganese oxide has demonstrated promising performance in various electrochemical reactions, including the NO_3RR .^{190,191} Likewise, Cu-based materials have exhibited significant outcomes in the electrochemical reduction of NO_3^- to NH_3 .^{192,193} As a result, incorporating copper into MnO catalysts could be a beneficial approach for enhancing the reaction efficiency. In their research, Jang *et al.*¹⁹⁴ produced a range of amorphous MnCuO_x catalysts with varying concentrations of oxygen vacancies using plasma treatments (Fig. 20a). OVs were detected using XPS and EPR analyses (Fig. 20d and e). The presence of a distinct peak at 531 eV in the oxygen 1s spectra and a strong signal around $g = 2$ in the EPR spectrum provided evidence for the formation of OVs. The higher intensity of the EPR spectrum for $\text{MnCuO}_x\text{-H}$ indicates a larger quantity of OVs following plasma irradiation. The MnCuO_x catalyst with a high concentration of OVs ($\text{MnCuO}_x\text{-H}$) exhibited a significant ammonia yield rate of 9.4 mg cm^{-2} h^{-1} and FE of 86.4%. The authors hypothesized that the OVs present in the catalyst contributed to a reduction in the binding energy of NO_3^- and a weakening of the N-O bond, leading to a superior performance. Similarly, a dual-site electrocatalyst for NO_3^- reduction was developed by Wang *et al.*¹⁹⁵ which was composed of $\text{MnO}_2\text{-O}_v$ nanosheets enriched with OVs, and Pd nanoparticles that were deposited onto 3D porous nickel foam ($\text{Pd-MnO}_2\text{-O}_v/\text{Ni}$ foam). XPS and EPR spectral studies revealed the presence of OVs. The $\text{Pd-MnO}_2\text{-O}_v/\text{Ni}$ foam exhibits a higher concentration of OVs than the Pd/Ni foam, with percentages of 35.25% and 26.75%, respectively (Fig. 20f and g). The electrocatalyst was found to be effective in adsorbing, immobilizing, and activating NO_3^- and other intermediates through the $\text{MnO}_2\text{-O}_v$ nanosheets, while the Pd provided sufficient adsorbed hydrogen (H^*) to the oxygen vacancy sites for both NO_3^- reduction and OV regeneration, as evidenced by experi-

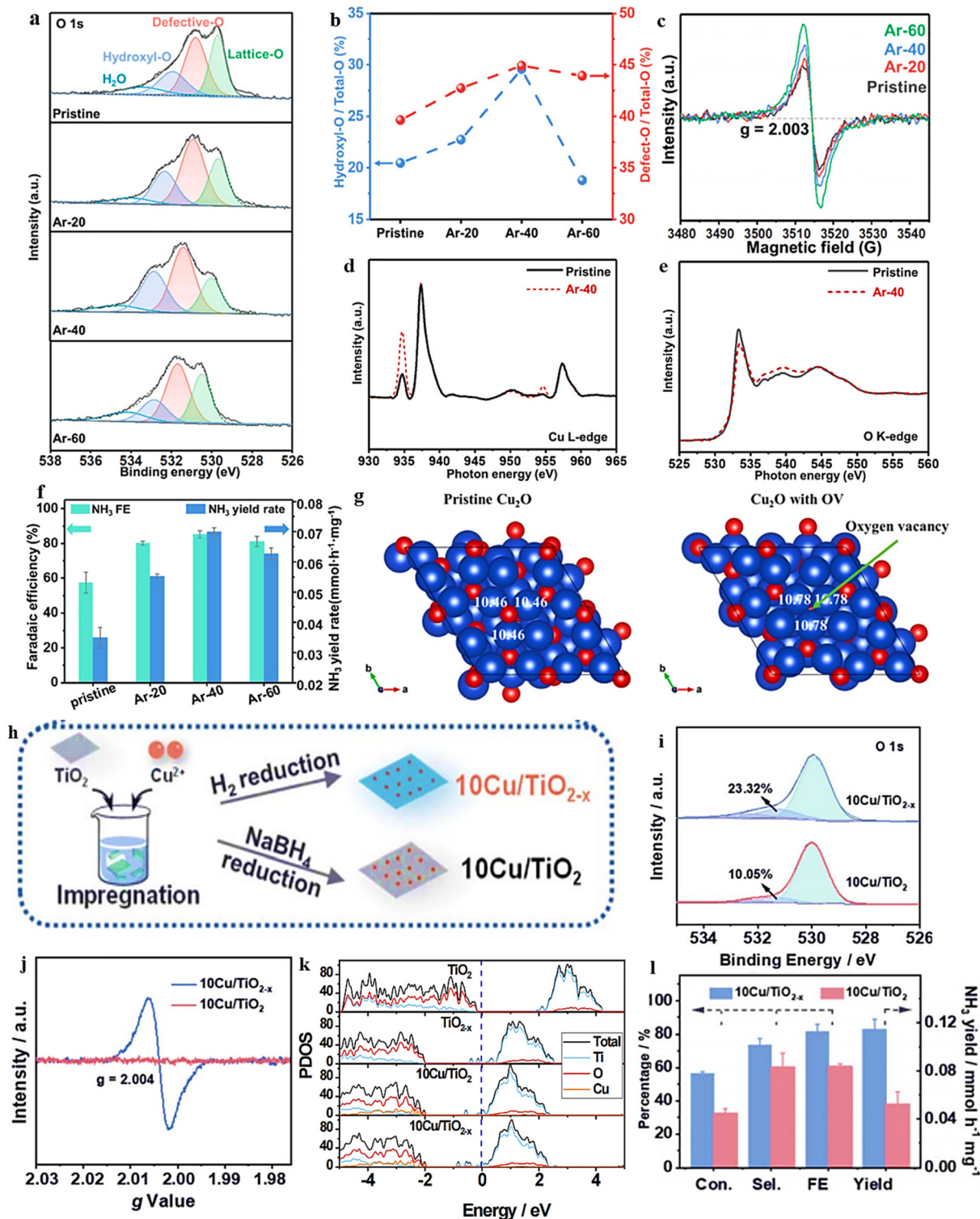


Fig. 18 (a) O 1s XPS spectra of pristine, Ar-20, Ar-40, and Ar-60. (b) The proportion of pristine, Ar-20, Ar-40, and Ar-60 areas that are occupied by O species. (c) The pure Ar-20, Ar-40, and Ar-60 EPR spectra. (d and e) X-ray absorption spectra (XAS) of pure Cu L-edge and Ar-40. (f) Ammonia production catalyzed by pristine Ar, Ar-20, Ar-40, and Ar-60 with 50 ppm N-NO₃⁻ at -1.2 V vs. Ag/AgCl for 6 hours: FE and yield rate. (g) Bader charge analysis was used to determine the polarization charge density before (left) and after (right) the creation of oxygen vacancies. Reproduced from ref. 169 with permission from Elsevier, copyright 2023. (h) Schematic presentation of the catalyst synthesis. (i and j) O 1s XPS spectra and EPR spectra of the prepared materials. (k) PDOS of the different materials and (l) 10Cu/TiO_{2-x} and 10Cu/TiO₂ for NO₃⁻ reduction at 0.75 V: conversion rate (Con), selectivity (Sel), FE, and NH₃ production rate. Reproduce from ref. 106 with permission from Elsevier, copyright 2023.

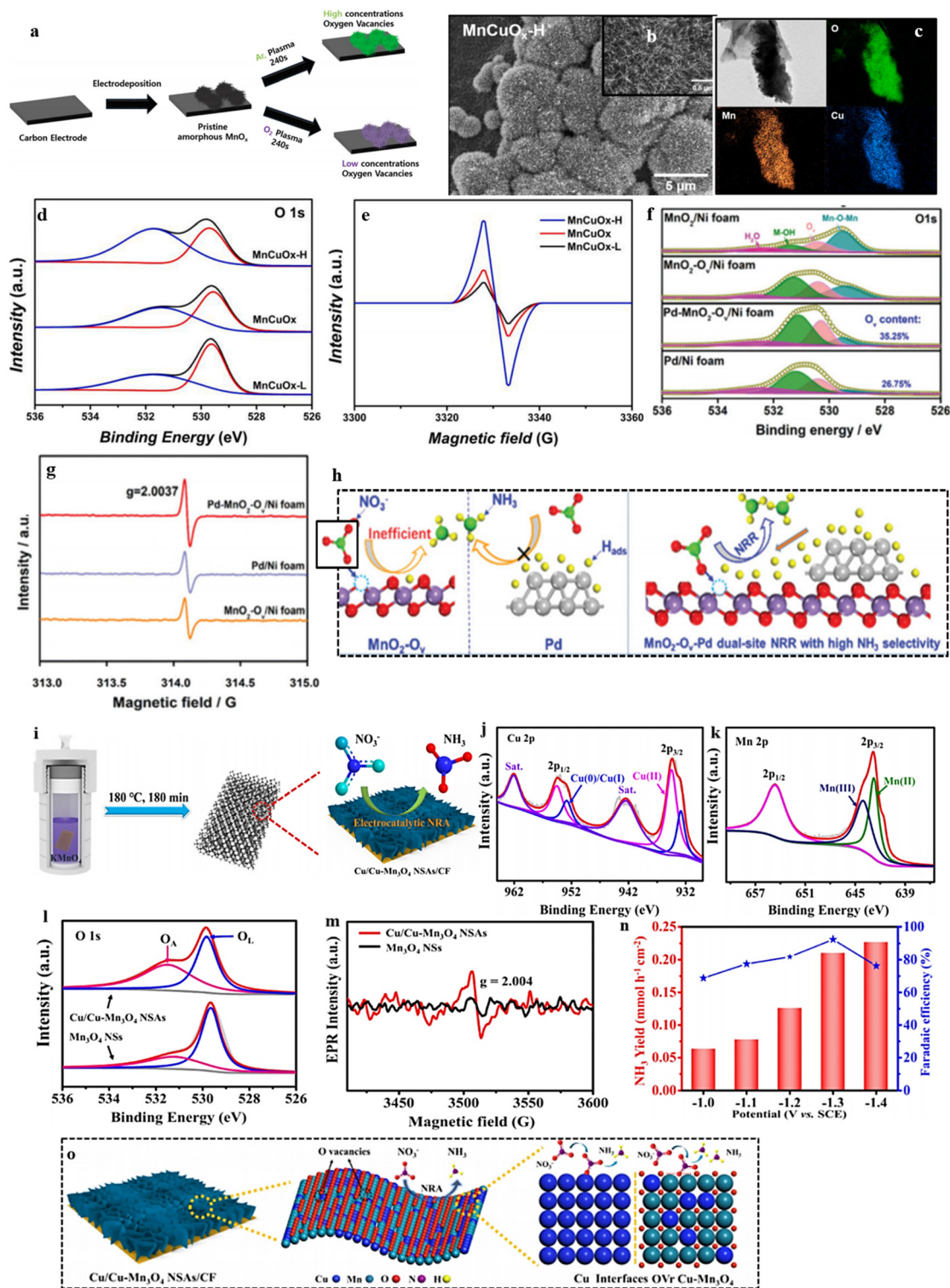


Fig. 20 (a) Illustration in the form of a schematic showing the complete synthesis process for MnCuO_x catalysts. (b) SEM morphology of $\text{MnCuO}_x\text{-H}$. (c) The elemental distribution of oxygen, manganese, copper, and their overlay in a selected area of $\text{MnCuO}_x\text{-H}$, as shown by EDX. (d and e) The XPS spectra of O 1s and the EPR spectra of the MnCuO_x catalysts. Reproduced from ref. 194 with permission from Elsevier, copyright 2023. (f and g) XPS analysis of O 1s of a PdMnO_2 sample and (h) a schematic of the high- NH_3 selectivity $\text{MnO}_2\text{-Ov-Pd}$ dual-site NRR mechanism. Reproduced with permission.¹⁹⁵ (i) Electrocatalytic NO_3^- reduction by $\text{Cu/Cu-Mn}_3\text{O}_4$ NSAs/CF: a preparation and illustration scheme. (j–l) XPS spectra of distinct Cu 2p, Mn 2p, and O 1s orbitals in various $\text{Cu/Cu-Mn}_3\text{O}_4$ samples. (m) EPR of $\text{Cu/Cu-Mn}_3\text{O}_4$ samples. (n) Production of NH_3 and FE at different potentials. (o) A schematic representation of the electrocatalytic reduction of NO_3^- to NH_3 conversion on $\text{Cu/Cu-Mn}_3\text{O}_4$ NSAs/CF. Reproduced from ref. 197 with permission from American Chemical Society, copyright 2021.

solution, with a production rate reaching a maximum of 55.29 mmol h⁻¹ (Fig. 21e). The NO_x⁻ in aqueous solution was employed directly as the catholyte for the second electroreduction process, using oxygen vacancy-rich Co₃O₄ nanoparticles as the catalyst. By utilizing DFT calculations, it was discovered that including OVs in Co₃O₄ nanoparticles enhances the activity of adjacent Co atoms. This, in turn, leads to an increase in the adsorption and hydrogenation of NO_x⁻ by reducing the Δ*G* of the rate-limiting step while simultaneously impeding the hydrogen evolution reaction (Fig. 21g and h). Consequently, these oxygen vacancy-rich Co₃O₄ nanoparticles exhibit an outstanding NH₃ production rate of 39.60 mg h⁻¹ cm⁻², a high faradaic efficiency of 96.08% (at -0.8 V), and a large current density of 376.48 mA cm⁻² (Fig. 21i). This study demonstrates the possibility of generating NH₃ from air sustainably for industrial purposes and inspires further innovation in the entire NH₃ production system. This includes the exploration of alternative reaction routes, the development of improved devices, and the discovery of novel catalysts. Similarly, metal doping and oxygen vacancies in transition metal oxides are believed to be effective in achieving high activity and NH₃ selectivity in the NO₃RR. To this end, Sam and colleagues¹⁹⁹ synthesized Cu-doped Co₃O₄ with abundant oxygen vacancies (Cu-Co₃O_{4-x}) on carbon cloth (Fig. 21j). The O 1s spectra of Cu-Co₃O_{4-x} were analyzed using XPS, and the results showed three peaks at 530.8, 531.9, and 533.5 eV (Fig. 21m). These peaks corresponded to lattice oxygen (O1), oxygen vacancy (O2), and surface-adsorbed oxygen species (O3), respectively.²⁰⁰ The Cu-Co₃O_{4-x} sample contained 25.9% OVs, which was considerably higher than the oxygen vacancy content of Co₃O₄ (17.2%), demonstrating that the increased concentration of oxygen vacancies was successfully achieved in Cu-Co₃O_{4-x}.

Similarly, Cu-Co₃O_{4-x} displays a more intense EPR signal than Co₃O₄, suggesting a higher concentration of oxygen vacancies in Cu-Co₃O_{4-x} (Fig. 21n). These findings provide conclusive evidence that Cu-Co₃O_{4-x} nanoarrays were effectively synthesized. The Cu-Co₃O_{4-x} produced in this study exhibited an excellent performance in selectively reducing nitrate to NH₃, achieving high faradaic efficiencies of approximately 90% and a substantial NH₃ yield of 0.83 mmol h⁻¹ cm⁻² in the neutral electrolyte (Fig. 21o). The authors attributed the greatly improved NO₃RR activity and selectivity towards NH₃ to both the Cu doping and the presence of abundant oxygen vacancies in the CuCo₃O_{4-x}. Moreover, the Cu-Co₃O_{4-x} sample with the greater active surface area among the Cu-Co₃O_{4-x} samples exposed more catalytically active sites, further contributing to its high NO₃RR activity.

5.1 Perovskite-based electrocatalysts

Owing to its exceptional catalytic activity, flexible structure, and composition, perovskite oxides have recently been recognized as a potential candidate for a new kind of catalyst material. Perovskite oxides, in contrast to other types of metal oxide, promote their metal cations in non-standard or mixed valence states, which results in an abundance of oxygen

vacancies in the structures of the catalysts. Perovskite oxides possess a unique characteristic, unlike other metal oxides, where the concentration of oxygen vacancies can be effectively controlled.⁵⁴ Doping at B-sites in ABO₃-typed perovskites has been demonstrated to enhance the electrocatalytic performance by increasing the presence of oxygen vacancies. Typically, the oxygen anions coordinated with B-sites exhibit higher reactivity for electrochemical reactions, as evidenced by prior studies.^{63,201} This potential inspired Zheng *et al.*⁸⁴ to investigate the performance of perovskite oxides in electrochemical nitrate reduction reactions. The researchers prepared four different ABO₃-type perovskite oxides (A = La; B = Cr, Mn, Fe, Co) with distinct crystal structures. Among the four perovskites (LaCoO₃, LaMnO₃, LaCrO₃, LaFeO₃), the O 1s XPS spectra revealed a prominent OV band at 531.3 eV,²⁰² with LaCoO₃ exhibiting the highest percentage at 47.1% (Fig. 22a and b). Furthermore, the investigation of OVs was also conducted using the EPR technique, revealing that LaCoO₃ exhibited a robust EPR signal, suggesting the highest percentage of oxygen vacancies compared with the other perovskites (Fig. 22c). Using density functional theory (DFT) analysis, it was discovered that incorporating OVs into the LaCoO₃ perovskite enhances the adsorption of *NO₂ intermediates and significantly lowers the energy barrier required for nitrate reduction to ammonia catalysis. This results in improved activity and selectivity. In comparison with LaCrO₃ (21.7%, 0.44 mmol mg⁻¹ h⁻¹), LaMnO₃ (49.1%, 0.88 mmol mg⁻¹ h⁻¹), and LaFeO₃ (78.4%, 3.54 mmol mg⁻¹ h⁻¹), the LaCoO₃ electrode has a higher faradaic efficiency of 91.5% and a greater NH₃ yield rate of 4.18 mmol mg⁻¹ h⁻¹ at -1.0 V (vs. RHE) (Fig. 22d and e).

Although perovskite oxides based on cobalt have shown a significant amount of potential in electrocatalysis,^{203,204} their ability to accelerate NO₃⁻ electrochemical reduction to generate NH₃ has not been explored. Liu *et al.*²⁰⁵ have addressed this by proposing an effective strategy to promote NO₃ER activity by adjusting the A-site deficiencies of cobalt-based perovskite oxides. To demonstrate this, they used a series of (Ba_{0.5}Sr_{0.5})_{1-x}Co_{0.8}Fe_{0.2}O_{3-d} (*x* = 0, 0.05, 0.10, 0.15, and 0.20) catalysts as a proof-of-concept, finding that their NO₃ER activity followed a volcano-like dependence on the *x* values, peaking at *x* = 0.15. With the increasing A-site cation deficiencies, the XRD data presented in Fig. 22g revealed a slight shift towards higher angles for the main peak associated with the (110) plane. The presence of OVs in the (BS)_{1-x}CF samples was determined using XPS analysis. Fig. 22h and i display the O 1s XPS spectra, which show a distinct peak at 530.9 eV alongside three other peaks, indicating the presence of surface-generated OVs.²⁰⁶ The percentage of OVs in BSCF, (BS)0.95CF, (BS)0.90CF, (BS)0.85CF, and (BS)0.80CF was approximately 38.0%, 39.9%, 49.6%, 53.4%, and 55.1%, respectively. These findings demonstrate a direct correlation between the amount of A-site cation deficiencies and the quantity of OVs. As anticipated, the introduction of A-site deficiencies resulted in significant changes to the physicochemical properties of the cobalt-based perovskite oxides. Specifically, the A-site deficiencies led to the creation of

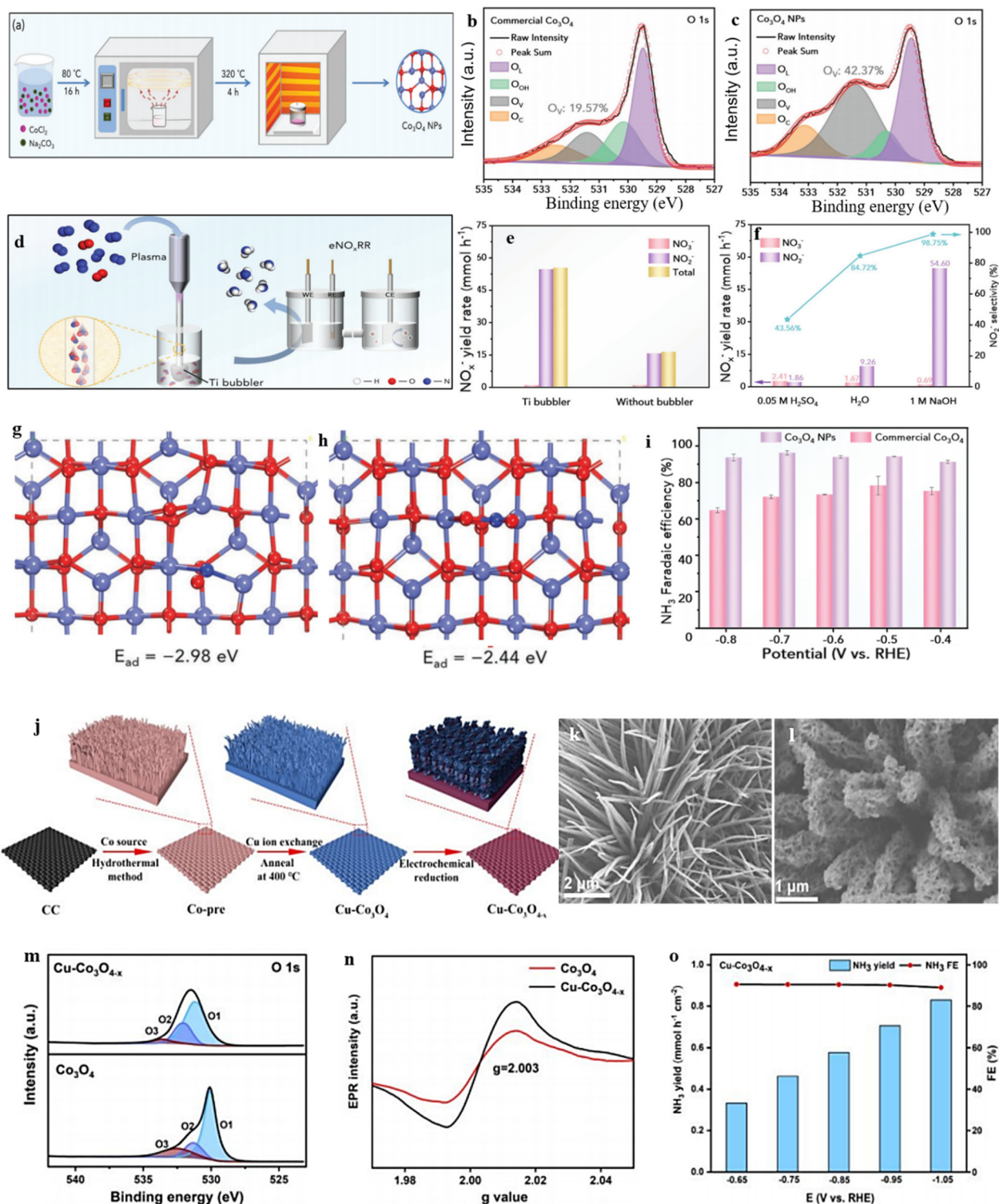


Fig. 21 (a) Schematic illustration of the preparation of Co_3O_4 NPs. (b) and (c) XPS spectra of Co O 1s for commercial Co_3O_4 and Co_3O_4 NPs respectively. (d) Complete system of N_2 fixation to NH_3 . (e) NO_x^- yield rate with and without a Ti bubbler in NaOH (1 M) absorption solution after 10 min plasma activation. (f) NO_x^- yield rate and NO_2^- selectivity absorbed by different solutions after 10 min plasma activation with a Ti bubbler. (g) and (h) Adsorption configurations and corresponding E_{ad} of NO_2^- on (g) OV- Co_3O_4 and (h) Co_3O_4 . (i) NH_3 FEs. Reproduced from ref. 198 with permission from Wiley, copyright 2023. (j) Schematic illustration of the synthesis process for $\text{Cu-Co}_3\text{O}_{4-x}$ on carbon cloth. (k) and (l) SEM images of $\text{Cu-Co}_3\text{O}_4$ and $\text{Cu-Co}_3\text{O}_{4-x}$ respectively. (m) and (n) XPS spectra of O 1s and EPR spectra of Co_3O_4 and $\text{Cu-Co}_3\text{O}_{4-x}$. (o) NH_3 yield rate and FE of $\text{Cu-Co}_3\text{O}_{4-x}$. Reproduced from ref. 199 with permission from RSC, copyright 2023.

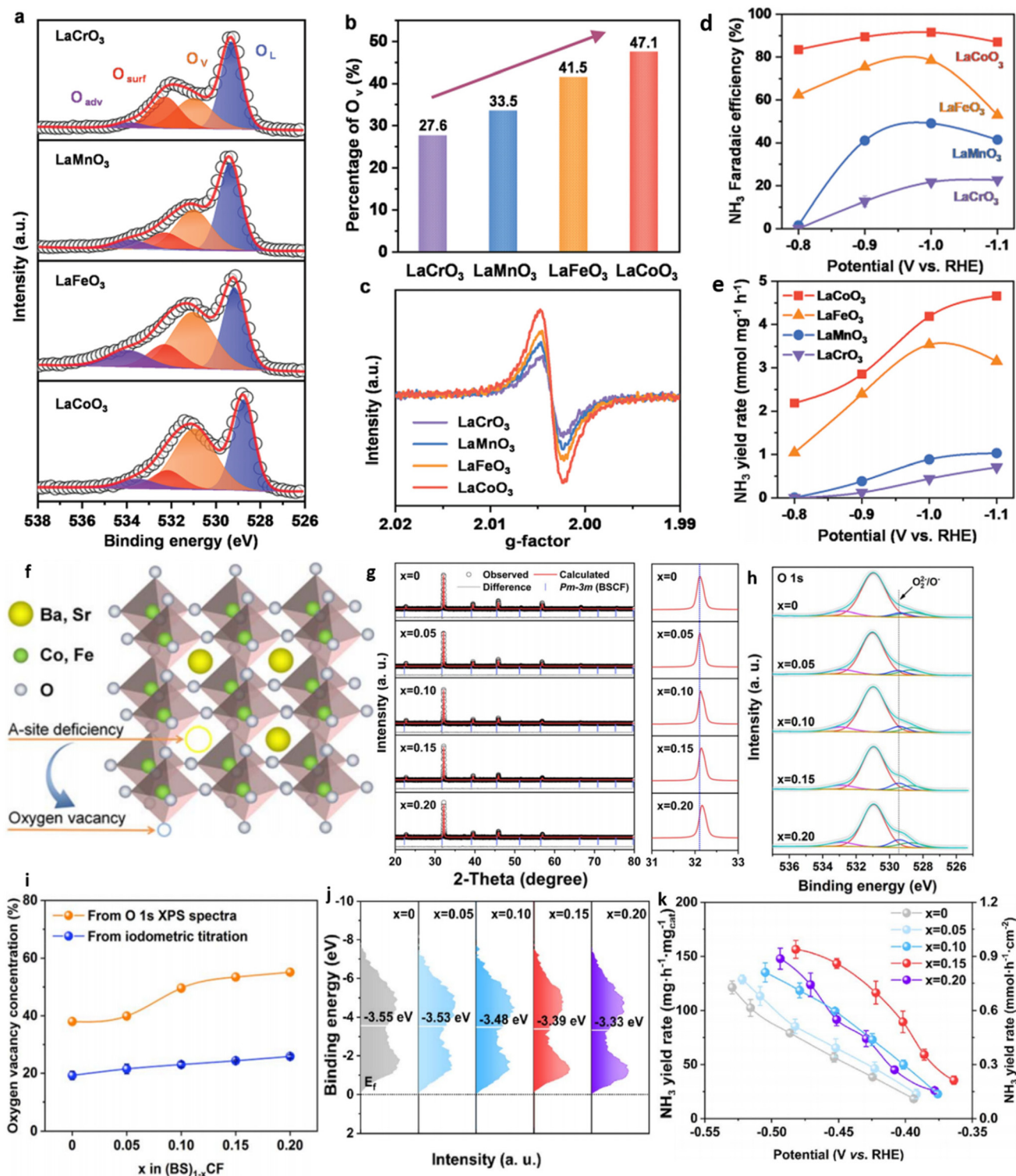


Fig. 22 (a) LaCrO₃, LaMnO₃, LaFeO₃, and LaCoO₃ O 1s spectra with high resolution by XPS analysis. (b) The percentage of oxygen vacancies for LaCrO₃, LaMnO₃, LaFeO₃, and LaCoO₃ from XPS analysis. (c) EPR spectra of LaCrO₃, LaMnO₃, LaFeO₃, and LaCoO₃. (d) NH₃ FE at different potentials, and (e) NH₃ yield rate at different potentials. With permission. (f) An illustration in the form of a schematic showing the formation of oxygen vacancies in A-site-deficient (BS)_{1-x}CF. (g) Rietveld refinement plots of (BS)_{1-x}CF sample XRD data with enlargements in the 2-theta region of 31–33°. (h) O 1s XPS spectra of the samples made from (BS)_{1-x}CF. (i) oxygen vacancy concentration. (j) XPS spectra of the surface valence bands, with the d band center determined. (k) The rate of NH₃ production by the (BS)_{1-x}CF samples at a variety of potentials. Reproduced from ref. 205 with permission from RSC, copyright 2023.

varying amounts of oxygen vacancies that increased with higher x values. Additionally, as x increased, the band center gradually shifted closer to the Fermi level (Fig. 22j). The results of this research pave the way for a hopeful approach toward the rational development of innovative cobalt-based perovskite oxides for facilitating NO_3^- ER catalysis. Among them, the (BS)0.85CF catalyst exhibited the highest activity ($143.3 \text{ mg h}^{-1} \text{ mg}_{\text{cat}}^{-1}$ or $0.86 \text{ mmol h}^{-1} \text{ cm}^{-2}$) and selectivity (97.9%) for ammonia at -0.45 V (vs. RHE), and maintained excellent stability for up to 200 hours, surpassing most previously reported NO_3^- ER catalysts (Fig. 22k).

The manipulation of the electronic structure, material properties, and catalytic efficiency has been attributed to the recognition of factors such as the 2D architecture, structural defects, and the interface effect.^{207–211} Taking inspiration from the aforementioned material characteristics, Wang *et al.*²¹² employed the chemical oxidation of Cu foam to produce an in-plane heterostructured nanosheet structure, Cu/CuO_x/CF, characterized by a high abundance of OV_s (Fig. 23a, d, and e). The authors suggested that the arrays of 2D nanosheets could offer a plentiful number of active sites and greatly improve the process of mass/charge transfer during electrocatalysis. Furthermore, the presence of in-plane heterojunctions and the high concentration of OV_s worked synergistically to enhance the electronic properties of the catalytic sites. As a result, it became possible to control the adsorption properties of reactant intermediates and minimize the generation of undesired byproducts. The excellent physicochemical characteristics of Cu/CuO_x/CF result in its outstanding catalytic performance for electrocatalytic NO_3^- -to- NH_3 conversion. Notably, the NH_3 yield rate on Cu/CuO_x/CF can achieve $0.23 \text{ mmol h}^{-1} \text{ cm}^{-2}$ at -1.3 V (vs. SCE), with an excellent NO_3^- conversion efficiency (99.52%), NH_3 selectivity (95.00%), and NH_3 faradaic efficiency (FE, 93.58%) (Fig. 23g, h, and i).

Tungsten (W) catalysts having OV_s are extensively utilized to enhance selective NH_3 synthesis. For instance, WO_{3-x} nanosheets and WO_{3-x} nanowires with OV_s can influence the adsorption of N species and mitigate the competing HER to some degree.²¹³ Consequently, it is expected that OV_s in W-based catalysts can efficiently capture and reduce N species. Nevertheless, there is a scarcity of research focusing on tungsten-based perovskite oxide (nanosheets) with OV_s for nitrate reduction to ammonia. A comprehensive investigation was conducted by Feng *et al.*²¹⁴ regarding the synthesis (Fig. 24a) and electroreduction of nitrate to ammonia using NbWO₆ nanosheets with oxygen vacancies (NbWO_{6-x}). The presence of oxygen vacancies was confirmed through XPS and EPR techniques, as illustrated in Fig. 24b and d. The analysis of the density of states (DOS) for NbWO₆ reveals that oxygen (O), niobium (Nb), and tungsten (W) make the most significant contributions to both the valence band and conduction band. Additionally, the DOS analysis demonstrates the presence of distinct defect energy levels in the conduction band of NbWO_{6-x}, indicating enhanced electron transitions (Fig. 24e). The introduction of oxygen vacancies on the surface results in the Fermi level shifting towards the CBM (conduction band

minimum) due to the acquisition of excess 4d electrons from tungsten (W). Consequently, this imparts metallic behavior to the NbWO_{6-x}, leading to improved conductivity, which is advantageous for electrochemical reduction. Moreover, the adsorption energy of NO_3^- on NbWO_{6-x} (-1.27 eV) is significantly lower compared with NbWO₆ (-0.53 eV), making it more favorable for NO_3^- adsorption (Fig. 24f). This enhanced adsorption capability facilitates nitrate reduction to NH_3 .

Nb-based materials have garnered considerable attention in heterogeneous catalysis due to their promising properties. Among them, NbO₂ is highly regarded for its semiconductor properties, exhibiting high capacitance and exceptional electrical conductivity.²¹⁵ Moreover, Nb₂O₅ has been identified as an effective catalyst for favorable ammonia synthesis, even under challenging conditions.²¹⁶ Consequently, Nb oxides hold great potential as electrocatalysts for nitrate to NH_3 conversion, as the d-orbitals (partially occupied) of Nb⁴⁺ facilitate π back bonding with reactants. Taking inspiration from these advantageous properties, Wan *et al.*²¹⁷ have recently presented pioneering research introducing an NbO_x catalyst containing OV_s for nitrate reduction to produce NH_3 . The XPS spectra of Nb₂O₅ exhibit a single peak at 530.5 eV, whereas NbO_x displays an additional peak at 531.8 eV, suggesting the presence of OV_s in the NbO_x sample (Fig. 24h).⁵⁷ Furthermore, the investigation conducted by PI demonstrated that the NbO_x sample contains a higher concentration of OV_s compared with the Nb₂O₅ counterpart (Fig. 24i). The OV-rich material demonstrated an impressive faradaic efficiency (FE) of 94.5% and achieved an NH_3 formation rate of $55.0 \mu\text{g h}^{-1} \text{ mg}_{\text{cat}}^{-1}$ (Fig. 24j and k). A detail investigation revealed that the presence of OV_s significantly influenced the chemical state of Nb, resulting in an enhancement of the binding energy of crucial intermediates during electrolysis.

Crystal facet engineering has been widely acknowledged as a means to adjust material properties and electrocatalytic efficiency. The use of catalysts with controllable crystal facets provides an excellent opportunity to investigate how catalyst properties influence surface reaction kinetics.^{218,219} In their study, Zhong *et al.*²²⁰ synthesized Cu₂O samples with various facets, including (100), (111), and a combination of (100) and (111) (Fig. 25a–c). These samples were prepared with different levels of oxygen vacancies and OH groups as observed from XPS investigations (Fig. 25d). Notably, Cu₂O with (111) facets demonstrated the highest presence of oxygen vacancies and hydroxyl groups on its surface. Based on their findings, the researchers concluded that on the Cu₂O(111) surface, the presence of OV_s improves the adsorption kinetics of reactants and other intermediates. At the same time, hydroxyl groups play a crucial role in inhibiting the unwanted hydrogen evolution side reaction and facilitating the reduction process of NO_3^- (Fig. 25g). The combined impact of these two factors is responsible for the exceptional NO_3^- reduction activity observed in the Cu₂O(111) facet when compared with other facets (Fig. 25j).

Although the role of OV and ion clusters has been studied in electrochemical catalysis, the synergistic interaction between these two species has received limited attention.

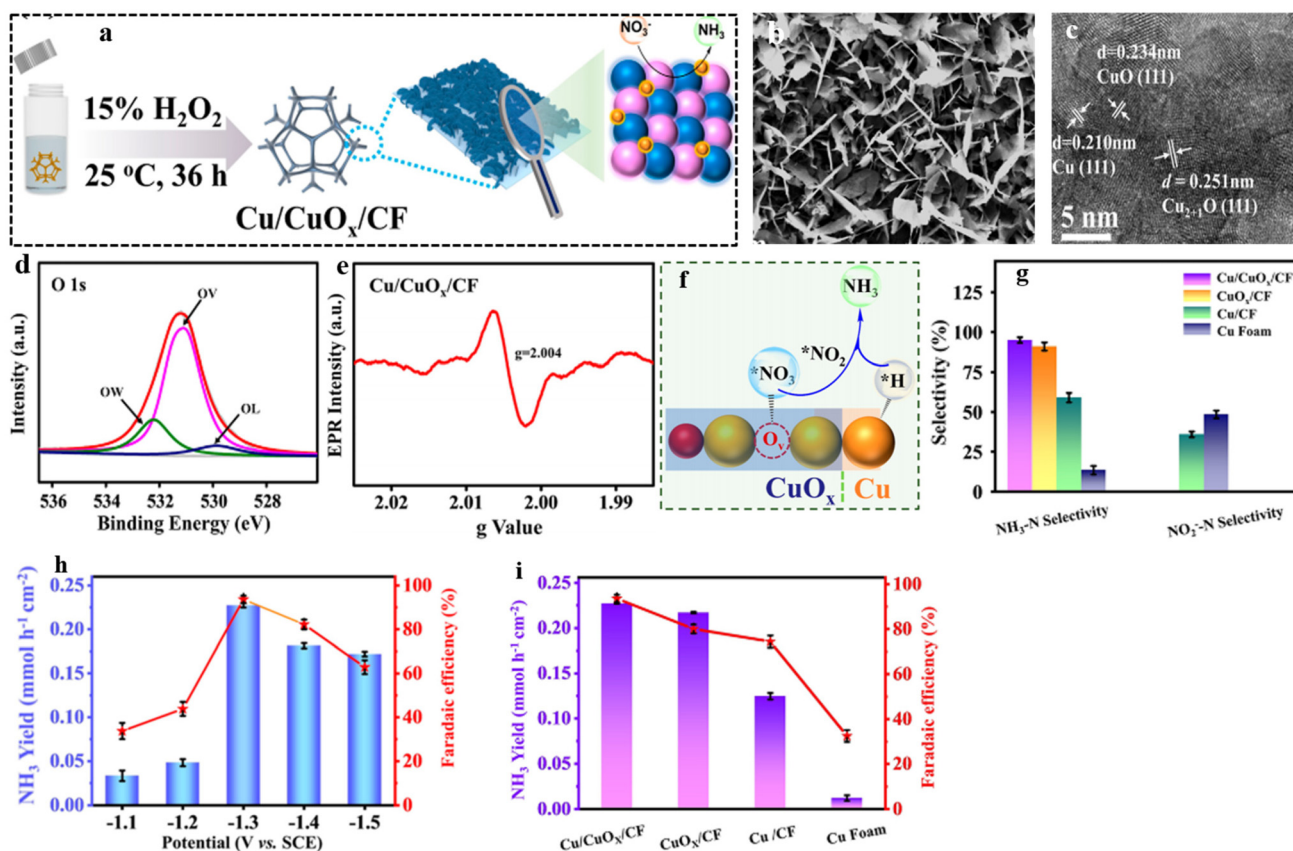


Fig. 23 (a) A schematic depicting the production of Cu/CuO_x/CF as well as its subsequent electroreduction using NO₃⁻. (b and c) Images of Cu/CuO_x/CF were obtained using SEM and HRTEM. XPS spectra of O 1s as item (d). (e) EPR spectra. (f) A schematic representation of the electrochemical reaction that converts NO₃⁻ to NH₃, which is catalyzed by the Cu/CuO_x/CF system. Selectivity of the NH₃-N and NO₂-N, yield rate, and the FE of NH₃ for various samples (g–i). Adopted with permission.²¹² With permission from the American Chemical Society, copyright 2022.

Chen *et al.*²²¹ developed a Cu-based electrocatalyst called Cu-Ov-W, which incorporates neighboring Mo clusters (Fig. 26a). The goal was to introduce asymmetric Ov properties to fine-tune the local electronic environment surrounding the active sites of the catalyst. The formation of OVs in CuW is supported by both XPS and EPR analyses (Fig. 26b and c). Notably, the hollow CuW (H-CuW) exhibits a higher intensity of OV compared with other counterparts, as confirmed by these investigations. The combined effect of the asymmetric Cu-Ov-W and the enhanced protonation process resulting from the Mo clusters contributes to a significant performance boost in the overall process. Consequently, this leads to a high Faradaic efficiency and yield rate of NH₃, achieving 94.60% and 5.84 mg h⁻¹ mg_{cat}⁻¹, respectively, at 0.7 V vs. RHE. According to DFT calculations, an elevated concentration of oxygen vacancies leads to a notable shift of the d-band center in CuW towards the Fermi energy (H-CuW, -3.36 eV and L-CuW, -3.79 eV) (Fig. 26d and e). The d-band centers are indicating that as the concentration of OVs increases, the d-band center moves closer to the Fermi energy. These upshifts in the d-band center highlight the essential role of the Cu-Ov-W sites in adjusting the local environment to favor the adsorption of NO₃⁻.

Additionally, this adjustment weakens and activates the N=O bond, thereby influencing the overall catalytic process.

5.2 Reaction mechanism from NO₃⁻ to NH₃

The electrochemical synthesis of NH₃ from NO₃⁻ proceeds through an eight-electron transfer reaction, with the oxidation states of the reactant changing from +5 in (NO₃⁻) to -3 in the product (NH₃).²²² The specific reaction pathway depends on various factors such as the catalyst composition, the current density, and the electrolyte environment.^{223–228} Several possible pathways for the electrochemical reduction of NO₃⁻ have been identified. One pathway involves the direct electroreduction of NO₃⁻ as shown in (Fig. 27a).^{229,230} This pathway has been observed on Pt- and Sn-based electrocatalysts, where the hydrogenation of adsorbed NO (NO_{ads}) occurs, leading to the formation of hydrogenated products such as HNO, H₂NO, H₂NOH, and finally NH₃ (Fig. 27c).^{229,230} Another pathway involves an H-assisted mechanism, where H₂O molecules are first reduced to generate adsorbed H (H_{ads}) (Fig. 27b).²⁰ The synchronized adsorption of H_{ads} and NO_{ads} leads to their hydrogenation and the formation of various hydrogenated

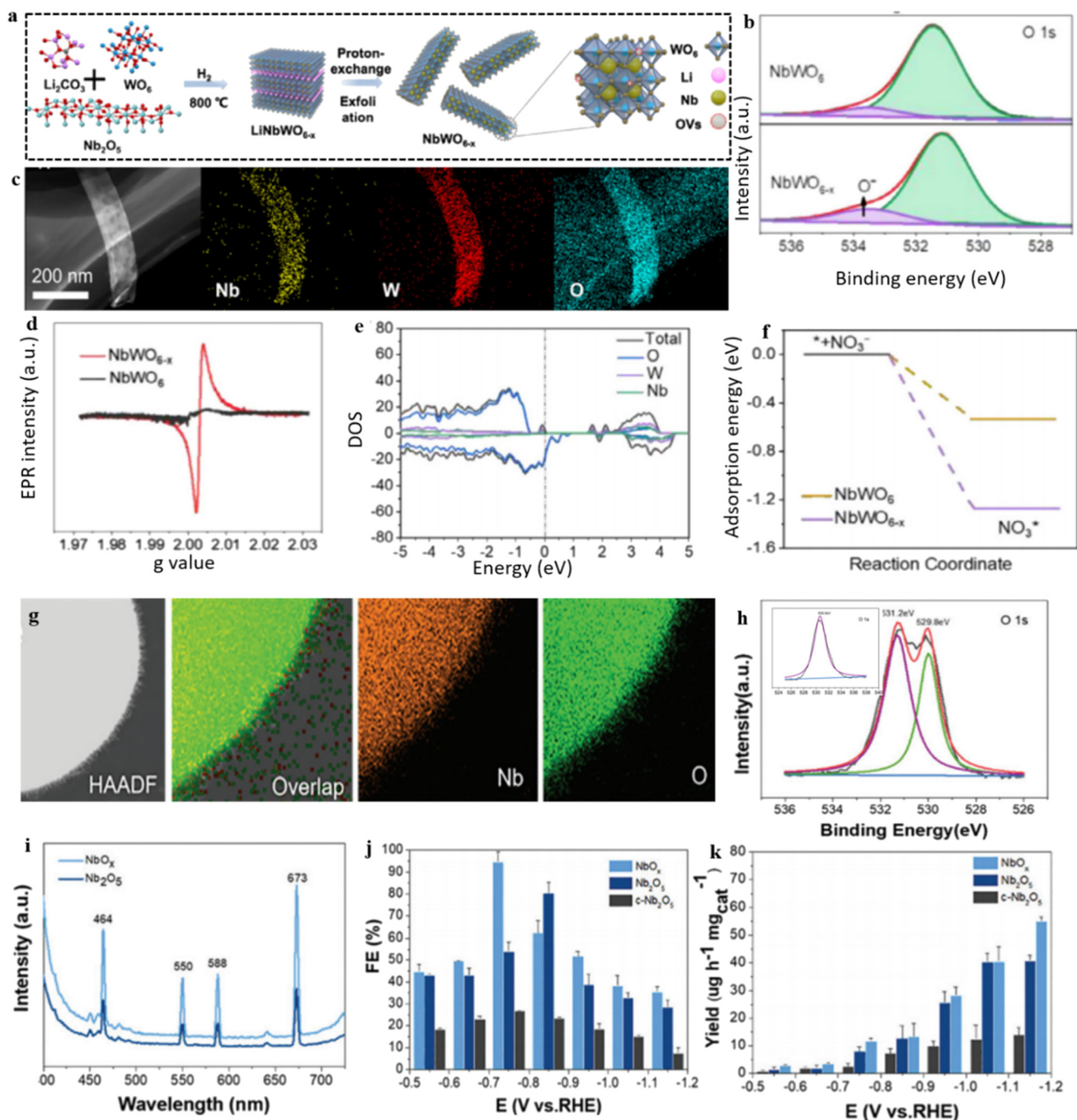


Fig. 24 (a) Schematic illustration of the NbWO_{6-x} nanosheet synthesis. (b) O 1s XPS spectra. (c) The HAADF-STEM picture of the NbWO_{6-x} nanosheets and their elemental mapping of Nb, W, and O. (d) EPR spectra, (e) The DOS diagram of NbWO_{6-x} and (f) calculated adsorption energies of NO_3^- on NbWO_6 and NbWO_{6-x} . Reproduced from ref. 214 with permission from Elsevier, copyright 2023. (g) EDX elemental mapping images of Nb and O for NbO_x . (h) O 1s XPS spectra of NbO_x and Nb_2O_5 (inset). (i) PL spectra of NbO_x and Nb_2O_5 . (j and k) Faradaic efficiency and NH_3 yield rates at different potentials. Reproduced from ref. 217 with permission from RSC, copyright 2022.

intermediates, ultimately resulting in NH_3 production (Fig. 27d).^{228,231,232} Ru-clusters have also been to support this mechanism by producing a reductive environment that facilitates the hydrogenation of NO_3^- .²⁰ The specific reaction conditions such as pH, concentration, and applied potential can influence the *in situ* reaction mechanism of electrochemical reduction of NO_3^- . For instance, under acidic conditions, NH_3

production increases while NO_2^- decreases. In alkaline conditions, the main product is observed as NH_2OH , but NO_2^- also appeared as well, indicating that the pathway can be pH-dependent.²³¹ Further studies, such as FTIR, have been conducted to investigate the detailed mechanism of NO_3^- reduction in the Cu(100) and Cu(111) facets in the presence of alkaline and acidic conditions. Likewise, the recent DFT

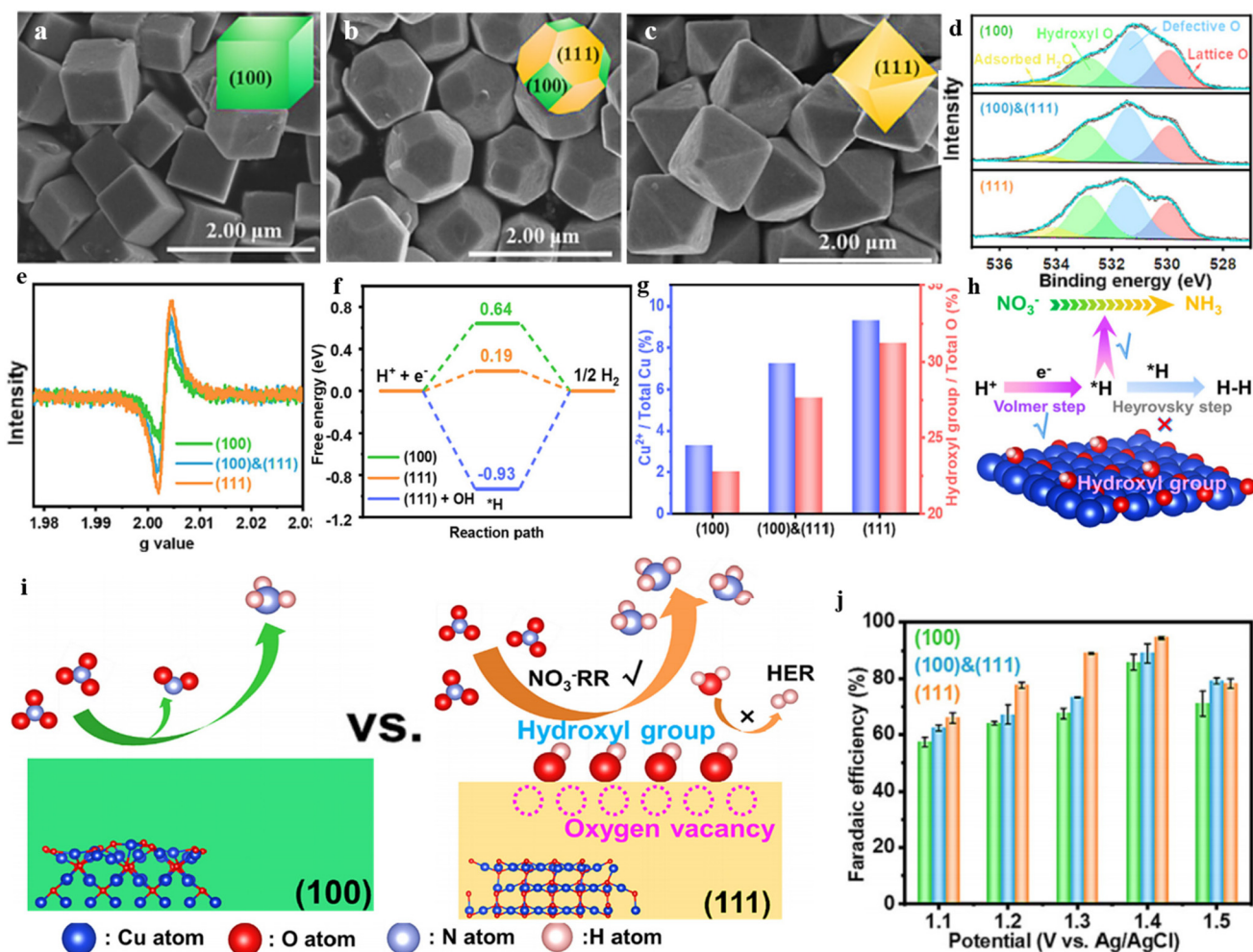


Fig. 25 (a–c) SEM morphologies (inset) of the exposed facet. (d) O 1s XPS. (e) EPR spectra. (f) A schematic illustrating the free energy of the HER as estimated by the DFT computation. (g) The percentage of Cu²⁺, which is shown on the left side of the y-axis, and the hydroxyl group, which is shown on the right side of the y-axis, on the surface of Cu₂O(100), Cu₂O(100) and (111), and Cu₂O(100) and (111). (h) A schematic illustrating how the presence of hydroxyl groups on the (111) facet could hinder the HER side reaction while simultaneously increasing hydrogenation in the NO₃RR. (i) Schematic representation of the surface oxygen species role in the NO₃RR to NH₃ reaction on the (100) facet (a) and the (111) facet (b). (j) FE for different aspects of the Cu₂O structure. Reproduced from ref. 220 with permission from Elsevier, copyright 2023.

analyses^{32,233} explained various reaction mechanisms involved in the electrochemical reduction of NO₃⁻. For example, DFT calculations for Fe single-atom catalysts proposed a mechanism where the hydrogenation of NO₃⁻ serves as the initiation step, followed by the reduction of intermediates, including NO₂⁻, HNO₂, NO, and the final product NH₃ (Fig. 27e).³² Transition metals have also been found to form NOH_{ads} as an intermediate precursor for NH₃ synthesis (Fig. 27f) during the electrochemical reduction process.²³³ This formation of NOH_{ads} occurs through H₂O-mediated hydrogenation of NO_{ads} which has a lower activation energy barrier compared with the dissociation of NO_{ads}. A similar mechanism has been reported for Cu-based solid catalyst, where NO_{ads} undergoes water-mediated hydrogenation to form NOH_{ads} (Fig. 27g).²³⁴ Yao *et al.*²³⁵ synthesized a Rh-based electrocatalyst and investigated the reaction intermediates in alkaline media *via* the use of surface-enhanced infrared-absorption spectroscopy and DEMS

analysis and observed N₂H₂ as an intermediate of NH₃ production. N₂H₂ can be further split into N₂ and NH₃ production, although the dissociation into H₂ and N₂ or further reduction remains uncertain. The adsorption energy of the electrochemical reaction intermediate NO_{ads} is one of the most essential parameters that affect the product distribution in the electrochemical reduction of NO₃⁻. Therefore the reduction of NO_{ads} is considered to precisely determine the selectivity of the reaction.^{236–238} Moreover, the theoretical analysis of NO reduction on various metals disclosed that the binding strength of NO* is uncovered to predict the reactivity of NO, which is an important intermediate step for the NO₃⁻ reduction.²³⁹ However, the supplied current density should also be carefully taken into consideration as a key parameter that can play a crucial role in influencing product distribution.²⁴⁰ The nature, composition, and applied potential of the electrocatalysts play a vital role in determining selectivity

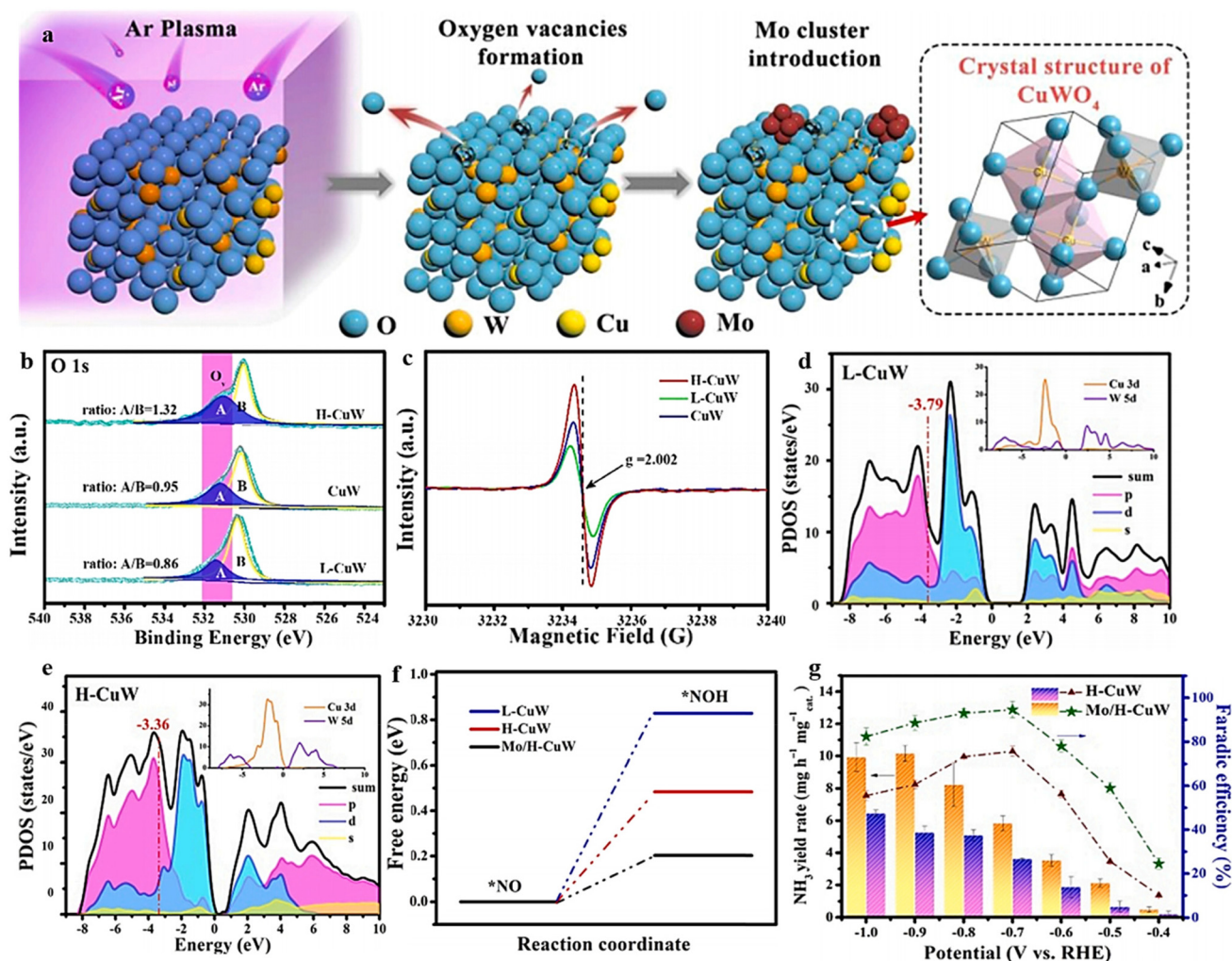


Fig. 26 (a) A diagrammatic representation of the steps involved in the Mo/H-CuW fabrication process. (b) and (c) show the XPS O 1s and EPR spectra of various materials. (d) PDOS of L-CuW and (e) PDOS of H-CuW, respectively. (f) A comparison of the changes in the Gibbs free energy that take place during the rate-determining step of NO_3RR for L-CuW, H-CuW, and Mo/H-CuW. (g) The rate at which NH_3 is produced as well as the FE of H-CuW and Mo/H-CuW. Reproduced from ref. 221 with permission from Elsevier, copyright 2023.

in the electrochemical reduction of NO_3^- . In the study of Jia *et al.*¹⁰⁵ OV s were introduced into TiO_2 to unveil the reaction mechanism for the selective generation of NH_3 . Different models of $\text{TiO}_2(101)$ surfaces were considered, including those with single OV s, two OV s, and without OV s. The density of states (DOS) analysis indicates that $\text{TiO}_2(101)$ without OV s exhibited semiconductor behavior. However, the introduction of OV s on the surface led to a switch in the Fermi level towards the conduction band minimum. This resulted from the excess 3d orbital electrons of Ti filling the OV s, giving rise to the metallic characteristic of TiO_{2-x} and improving the conductivity. This improved conductivity is beneficial for the electrochemical reduction reaction. The adsorption energy of NO_3^- on the surface of $\text{TiO}_2(101)$ was investigated for different configurations. It was found that $\text{TiO}_2(101)$ with a single inserted OV (-1.44 eV) or two OV s (-1.54 eV) showed much higher adsorption energy as compared with $\text{TiO}_2(101)$ without OV s (-0.71 eV) (Fig. 27i). This indicates a stronger binding of NO_3^-

on TiO_2 surfaces with OV s. The reaction Gibbs free energy (ΔG) of NO_3^- was calculated for different configurations.

In the case of NO_3^- adsorption on the surface of $\text{TiO}_2(101)$ in the absence of OV, as shown in (Fig. 27j), the NO_3^- O1 makes bond-coordination *via* unsaturated Ti, while O2 and O3 are shown exposed to the ambient reaction environment. The NO_3^* is hydrogenated and formed HNO_3^* , in this case, H makes a bond with O3 which is the most suitable active site as compared with O1 and O2. The hydrogenation process continues, another proton-electron pair is caught by O3, and the previous intermediate HNO_3^* leaves H to form NO_2^* and a water molecule. NO_2^* is automatically transformed to make NO_2 or HNO_2 , thus further hindering the reduction of NO_2^* . Considering $\text{TiO}_2(101)$ with the insertion of a single OV, the O1 of the NO_3^* can participate in filling the OV site, and the O2 makes a bond with its neighboring unsaturated Ti (Fig. 27k). N-O1 bond is broken by adsorbing a proton-coupled with an electron with an energy release of 2.10 eV. Similarly,

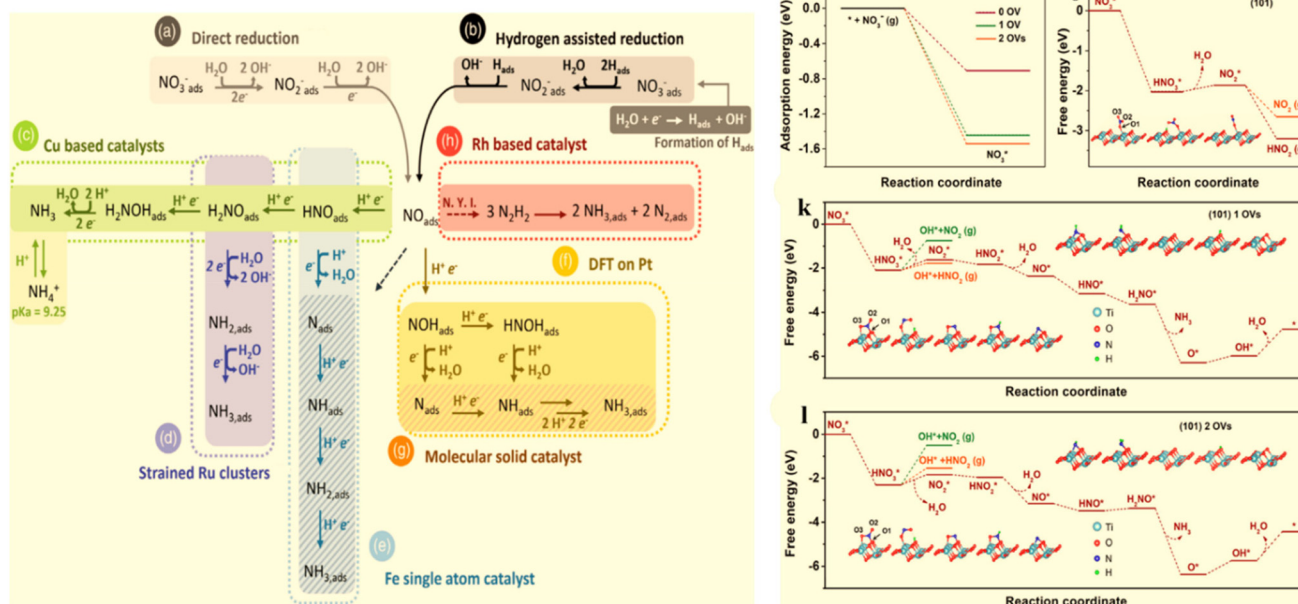


Fig. 27 (a–h) Proposed reaction pathways for ammonia synthesis reported by various latest literature reports.²⁴¹ (i) Nitrate adsorption energies on the surface of TiO₂(101) via zero, one and two OVs, (j) without OVs, (k) with one OV, and (l) two OVs at 0 V vs. RHE.¹⁰⁵ With permission from the American Chemical Society, copyright 2020.

O3 is attacked at a second proton–electron pair, making a coordination with an uphill energy change of 0.47 eV, and creates NO₂*. The possible probability of making HNO₂ byproducts with a smaller amount of energy release is 0.31 eV. N further activates and adsorbs the third proton to form HNO₂*. In a similar vein, O2 is released by the fourth hydrogenation step to form NO*. Moreover, three proton–electron pairs couple *via* N to form NH₃ gas, which leaves O1 on the OV site. Finally, O1 will be reduced by two protons to form water, recovering the oxygen vacancy on the surface. For TiO₂ (101) with two vacancies, the nitrate reduction process is similar to that on one vacancy surface in (Fig. 6l), but in the form of two OVs on the surface of TiO₂(101), requiring a higher reaction barrier for HNO₂, and therefore inhibiting the undesired byproducts. In summary, OVs not only involve filling *via* oxygen in NO₃⁻ to lose the oxygen–nitrogen bond but also motivate the interaction of the NO₃RR intermediate and catalysts to control the reaction pathway and suppress the synthesis of parasitic byproducts.¹⁰⁵

6. Conclusion, challenges, and perspectives

In conclusion, this review provides a comprehensive exploration of recent research advancements in catalysts focused on oxygen vacancies (OVs) and their critical role in the electrocatalytic conversion of NO₃⁻ into NH₃. This approach holds significant promise in its ability to surmount low energy barriers, address energy-related challenges, and make notable contributions to environmental sustainability. At the outset,

our attention was directed toward elucidating the techniques for examining oxygen vacancies (OVs) in catalysts primarily based on metal oxides. Notably, we emphasized methods such as X-ray absorption spectroscopy (XAS), X-ray photoelectron spectroscopy (XPS), electron paramagnetic resonance (EPR) spectroscopy, and positron annihilation spectroscopy (PAS). Subsequently, we explored the methods frequently employed to generate OVs. The induction of OVs has been shown to effectively control the electronic properties, mitigate undesirable reactions, and enhance the catalytic activity for NO₃⁻ reduction. This technique opens new possibilities for the development of high-performance catalysts. However, there are still unresolved scientific inquiries that require further investigation to fully understand the significance and function of OVs in this context.

In terms of achieving a precise and controllable generation of OVs, it is important to modulate the contents of OVs and manipulate the position of defects in materials. This can be done to induce changes in the adsorption energies of intermediates and surface electronic configurations, ultimately impacting the overall performance of catalysts. The concentration of defects also plays a pivotal role in determining the effectiveness of OVs. While a low defect concentration may not yield significant improvements, an excessive number of defects can lead to structural distortion and impede further improvements in conductivity by restricting charge mobility. Recent studies have focused on the production of defective metal oxides, and researchers have reached a unanimous conclusion that the concentration of surface OVs in the oxides increases with prolonged plasma treatment. This increase in

OVs leads to alterations in the chemical state, a decline in crystallinity, and reduced conductivity.^{47,243,244} However, an important question arises: is there a trade-off between the content of OVs and the catalytic behavior of defective catalysts? The mechanism by which an excessive quantity of OVs can trigger alterations in crystal structure and hinder charge transfer remains elusive and has yet to be fully understood. To address the aforementioned question, it is imperative to address these apprehensions, as they can contribute to a more comprehensive comprehension of the alterations in bulk and surface electronic distribution resulting from defects.

When considering the applicability of electrocatalysts for industrial applications, the stability of these catalysts becomes a crucial factor alongside their overall performance. However, a notable concern arises regarding the stability of OVs in different electrolyte environments. Although earlier studies have demonstrated the resilience of surface OVs under mild conditions through extensive long-term tests and *in situ* analysis,¹¹¹ their stability under harsh conditions remains a challenge. For instance, in highly alkaline media (1 M KOH), several studies have reported the disappearance of unsaturated vacancies, attributed to the replenishment influences of OH⁻ species present in the solution.²⁴⁵ Additionally, the diffusion of O₂ can catalyze the oxidation of surface OVs, thereby impeding optimal electrocatalytic activity.⁵⁷ Furthermore, there is still a lack of comprehensive understanding regarding how factors such as electrolyte composition and catalyst assembly influence the stability of OVs. Several investigations have also revealed the mobility of OVs within the bulk of a metal oxide.^{246,247} The continuous relocation of these OV defects can potentially lead to the development of microcracks in the catalyst.²⁴⁸ When OVs are generated through H₂ treatment, the concurrent formation of surface OH groups and H₂ impurities is consistently observed. The presence of these impurities can impact the electronic behavior of MOs,^{249,250} making it challenging to differentiate the specific effects attributed to oxygen vacancies from other potential factors.

The intermediate states of oxygen-defective MOs during these cycling processes remain unknown. Furthermore, surface OVs can activate dissolved O₂, leading to the formation of superoxide radicals.²⁵¹ These radicals can hinder the NO₃RR at the cathode.²⁵² Therefore, it is essential to gain a thorough understanding of the mechanistic effects of variables such as pH, dissolved O₂, and temperature on the stability of OVs, as well as their impact on the overall electrocatalytic reaction. This knowledge is particularly crucial due to the significant fluctuations of these variables in real wastewater streams. Furthermore, it is important to note that OVs could potentially introduce transitional layers within the electrocatalyst, especially in highly acidic or alkaline electrolytes. These transitional layers influence reaction pathways, which in turn impact the adsorption of intermediates and the rate-limiting steps. In addressing these complexities, there is a critical need for *in situ* characterization techniques that provide unequivocal evidence and in-depth insights into the reaction mechanisms. Methods like *in situ* Fourier-transform infrared spectroscopy

(FTIR), *in situ* Raman spectroscopy, and *in situ* X-ray absorption fine structure (XAFS) spectroscopy offer real-time observations that can illuminate the dynamic interplay of OVs and NO₃RR mechanisms.

Despite these advancements, the current catalyst materials' performance falls short of seamless industrial application, warranting further refinement. A promising path lies in the integration of experimental observations and theoretical insights. This synergy has the potential to yield enhanced, durable, and cost-effective electrocatalysts for NO₃RR. By merging experimental findings with theoretical predictions, a comprehensive understanding can emerge, ushering in a new era of electrocatalytic platforms for NO₃RR that are both sustainable and industrially feasible.

Data availability

The data that support the findings of this review are available from the corresponding author upon reasonable request.

Conflicts of interest

The authors declared that there is no conflict of interest.

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