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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 (NH₃) is a crucial chemical commodity used extensively in fertilizer production and as a renewable potential energy carrier. Conventionally, NH₃ 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 NH₃ synthesis *via* nitrate (NO₃⁻) and water, creating a sustainable environment. The electrochemical nitrate reduction reaction (NO₃RR) emerged as a promising eco-friendly alternative, boasting reduced energy consumption and mild reaction conditions. Moreover, the NO₃RR is capable of achieving a high NH₃ 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 NO₃RR. 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 NO₃RR, aiming to accelerate the development of exceptional electrocatalysts and contribute to a sustainable future for ammonia generation.

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1. Introduction

Ammonia (NH₃) 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 NH₃ 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 NH₃ synthesis to replace the conventional approach. Among the various options available, the NO3RR 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 N₂ to produce NH₃.⁹⁻¹³ 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 NH₃ production. 17,18 These obstacles arise due to the exceptionally high decomposition energy of the triple bond in N₂ (941 kJ mol⁻¹) and the limited solubility of N_2 in water.^{19–22} Furthermore, the dissociation of the first bond in N≡N necessitates an energy input of 410 kJ mol⁻¹, rendering the activation of N₂ exceptionally challenging and energetically demanding. Similarly, the electrochemical conversion of N2 to NH3 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 νs . 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 NH_3 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 NO_3RR to yield valuable NH_3 . 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. 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 NO_3RR .

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

$$NO_3^- + 6H_2O + 8e^- \to NH_3 + 9OH^-$$



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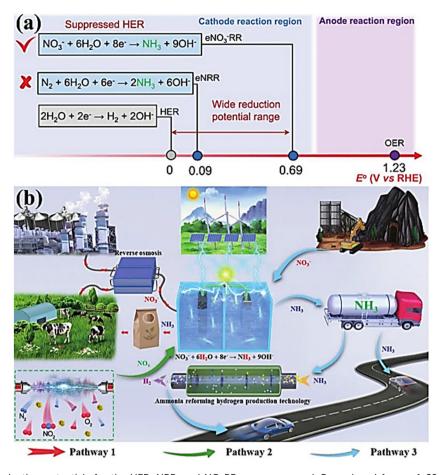


Fig. 1 (a) The standard reduction potentials for the HER, NRR, and NO_3RR were compared. Reproduced from ref. 29 with permission from the American Chemical Society, copyright 2022. (b) The design schematic illustration of the NO₃RR process to NH₃. Reproduced from ref. 33 with permission from Wiley, copyright 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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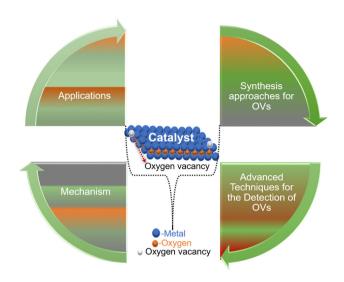
performance.

towards devising and fabricating electrocatalysts for use in the electrochemical NO₃RR to enable efficient NH₃ 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 NO₃⁻ 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 NO₃⁻ 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 CO₂RR, 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 O2, H2O, and H2, 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 NO₃⁻ reduction.⁶⁸ Hence, a comprehensive exploration of the impact of OVs on the electrocatalytic NO₃RR and its intermediates is imperative to guide the design of catalysts with superior catalytic

Our review covers the literature on the use of metal oxides as electrocatalysts, specifically focusing on the OVs for the NO₃RR to NH₃ 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 CO2 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 CeO2, 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 CO2 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 NH₃. 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 NO₃⁻ to NH₃. Furthermore, we have provided a concise overview of the catalytic mechanism underlying the heightened activity of OVs in NO3 reduction reactions. Additionally, we have outlined prospective advancements, challenges, and potential developments associated with the utilization of OVs in electrochemical NO₃ reduction. To the best of our knowledge, a comprehensive review dedicated to the electrochemical conversion of NO₃RR to NH₃ 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 NO₃RR 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 NO₃RR 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 NO₃RR, 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.

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 ${\rm O_2}^-$ anion in the regular lattice is substituted 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 metaloxygen 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

$$O_0^X \Leftrightarrow 0.5O_2 + 2e' + OV$$
 (1)

$$O_0^x \Leftrightarrow 0.5O_2 + e' + OV$$
 (2)

$$O_o^x \Leftrightarrow 0.5O_2 + OV$$
 (3)

The expressions used in the Kröger-Vink notation, where O₀ 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 $\Delta G_{\rm f}$ and equilibrium constant (K) of the defect reaction, as shown in eqn (4).^{37,86}

$$K = \frac{[V_{\ddot{O}}] \times p(O_2)^{0.5}}{[O_o]} = \exp\left(\frac{-\Delta G_f}{K_B T}\right)$$
(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.

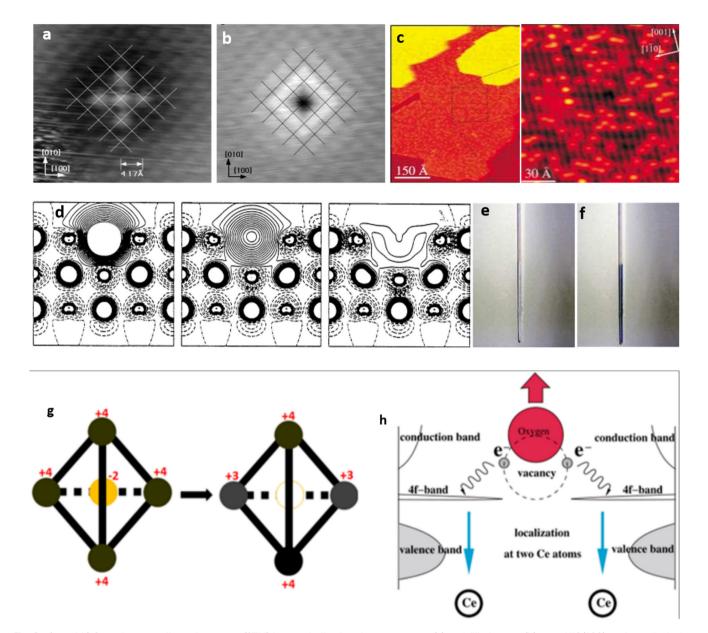


Fig. 2 (a and b) Scanning tunneling microscopy (STM) images indicating the empty state (a) and filled states (b) on a NiO(100) surface, disclosing the availability of vacancies. Reproduced from ref. 83 with permission from the American Physical Society, copyright 2022. (c) STM observation illustrating 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 F² 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.

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 CaMnO₃ (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 HfO2 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 Vd-V2O3. The results revealed that the V component in Vd-V₂O₃ has a higher oxidation state than c-V₂O₃, as indicated by the edge spectra observed at the B-site in Fig. 4f. The presence of vanadium vacancies in Vd-V₂O₃ might contribute to the elevated levels of V4+, increasing the oxidation state of vanadium. As depicted in Fig. 4f (site A), the intensified preedge band indicates a reduction in the local symmetry in the Vd-V₂O₃ sample. This observation suggests that the structure of Vd-V₂O₃ experiences distortion around the vanadium atoms due to the lack of neighboring atoms. In contrast to XANES,

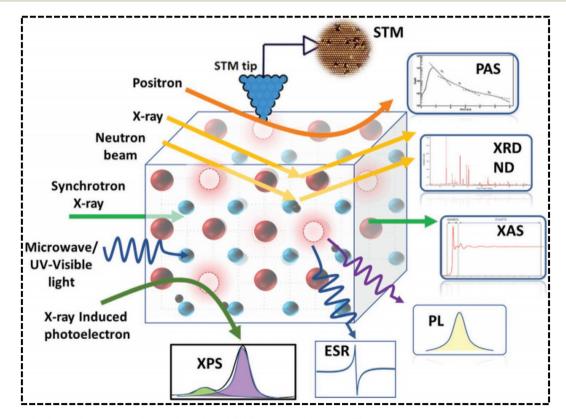


Fig. 3 A characterization technique used for the detection of OV. Reproduced from ref. 73.

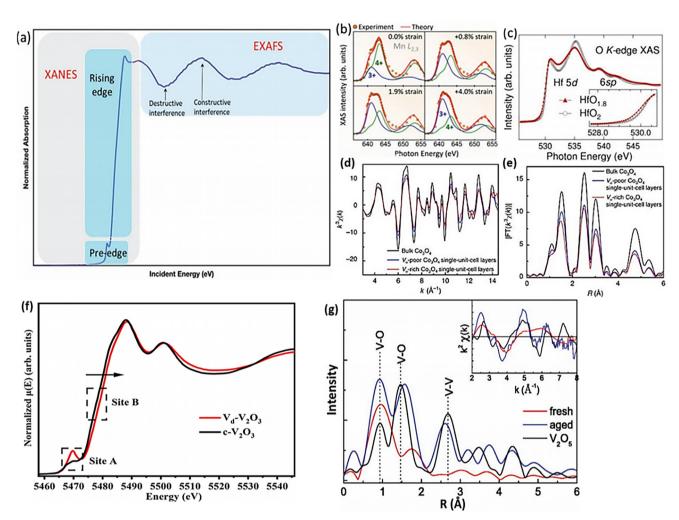


Fig. 4 Presents various XAS analyses used for characterizing OVs in metal oxides: (a) the typical profile of the XAS. Adapted with permission.⁹⁴ (b) The XANES of a Mn L-edge under different strains. Reproduced from ref. 95 with permission from the American Chemical Society, copyright 2017. (c) The XANES of an O K-edge of HfO₂ with OVs. Reproduced from ref. 97. (d) and (e) EXAFS oscillation and the corresponding Fourier transforms of VO-rich Co_3O_4 and VO-poor Co_3O_4 single-unit-cell layers. Reproduced with permission. 98 (f) Normalized XANES spectra of a V K-edge for Vd- V_2O_3 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 Vo 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 OVs 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 OVs, the electron that is compensated in OV can exhibit different behaviors depending on the concentration of OVs 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

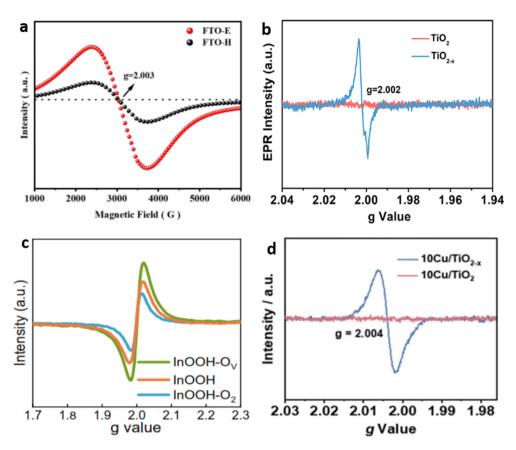


Fig. 5 Displays the EPR spectra of (a) FTO prepared by electrospinning and hydrothermal methods. Reproduced from ref. 103 with permission from Wiley, copyright 2022. (b) Prisitine TiO₂ and TiO₂ nanotubes. Reproduced from ref. 105 with permission from the American Chemical Society, copyright 2020. (c) Indium oxyhydroxide with different vacancies. Reproduced from ref. 22, and (d) Cu cluster deposited TiO₂. 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 TiO2 nanotubes, 105 Cu cluster TiO2, 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 OV-MoO₃/Ce samples. 109 Upon the inclusion of OVs through Ce doping, the binding energy of Mo in the OV-MoO₃/Ce spectra demonstrates a declining pattern, suggesting the reduction of some Mo⁶⁺ to Mo⁵⁺. The ratio of Mo⁵⁺ to Mo⁶⁺

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 Mo5+ is considered a reliable indicator of the relative abundance of OVs; thus, a higher Mo5+ 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 OV-MoO₃/Ce, in contrast to OV-MoO3, signifies the higher concentration of OVs in the OV-MoO₃/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 3d5/2 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 O2 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 Co2+ and Co3+ ratio in Co3O4 was also examined before and after plasma treatment. 60 The deconvoluted Co 2p

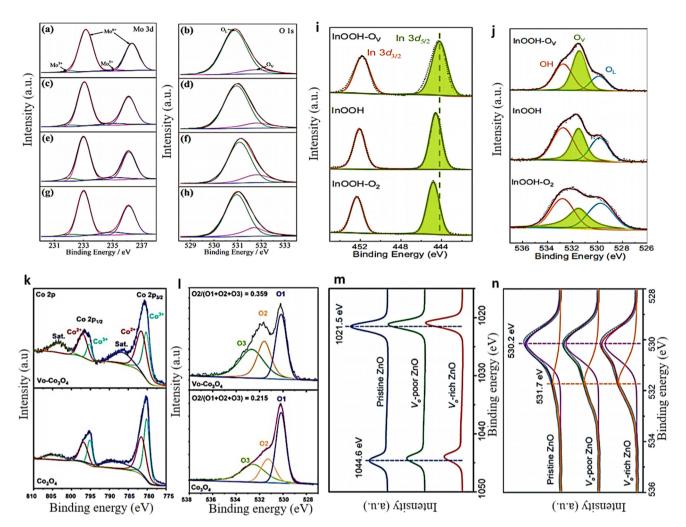


Fig. 6 (a and b) Mo 3d and O 1s deconvolution using XPS in OV-MoO₃. 1 (c and d) XPS analysis of OV-MoO₃/Ce = 40/1 indicates 0.62% doped, (e and f) OV-MoO₃/Ce = 30/1, and (g and h) OV-MoO₃/Ce = 20/1, respectively. Reproduced with permission.¹⁰⁹ (i and j) The corresponding HR-XPS spectra of 3d and O1s of InOOH. Reproduced with permission. 2(k and l) VO-Co_xO₄ and Co_xO₄ Co 2p and O1s 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 (2p1/2 and 2p3/2) 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 metalorganic 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 timeresolved 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, $\tau 1$ and $\tau 2$, which correspond to different defects

found in the samples. The smaller lifetime $(\tau 1)$ 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 Bi₂₄O₃₁Br₁₀ 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 BiVO₄ 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 quantification of the charge distribution associated with these vanadium vacancies.

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,

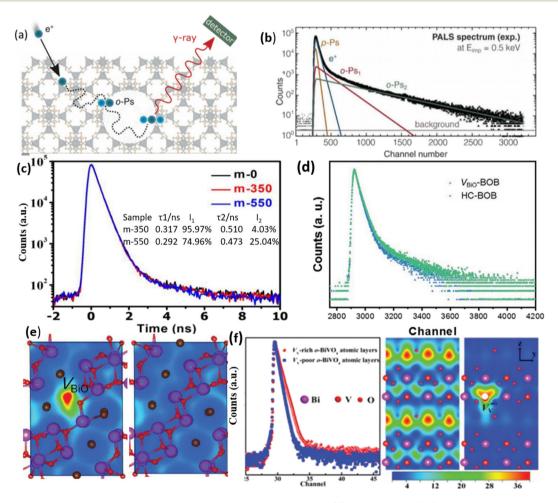


Fig. 7 (a) Positron annihilation model depicted schematically within a porous cave. (b) Analysis of the PAS spectrum and fitting of various degradation processes. Reproduced from ref. 117 with permission from Wiley, copyright 2021. (c) These are the positron annihilation spectra of samples of m-0, m-350, 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; I1 and I2 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 Bi₂O_{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 absorption 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/TiO2 samples were synthesized by Qian et al.130 by subjecting Ti₃C₂ 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-

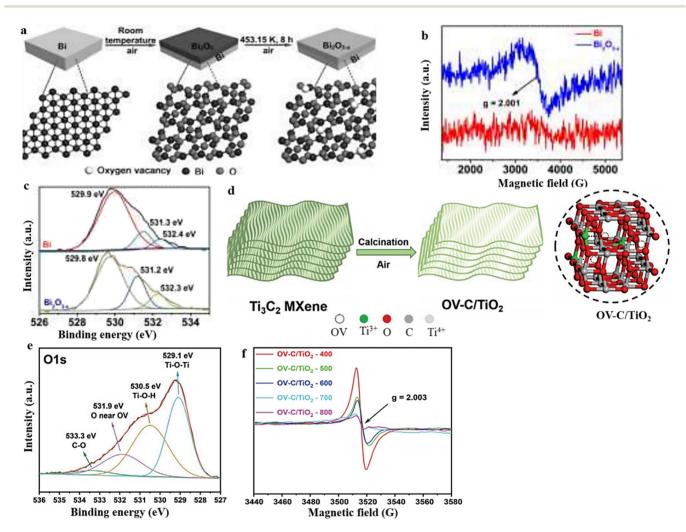


Fig. 8 (a) An illustration of the schematic process for the production of a layer of Bi_2O_{3-x} with oxygen vacancies. (b) and (c) EPR and O 1s XPS spectra of Bi₂O_{3-x}. Reproduced from ref. 127 with permission from Wiley, copyright 2020. (d) Diagram of the preparation process of OV-C/TiO₂. (e) and (f) The O 1s XPS and EPR spectra of OV-C/TiO2. 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 OVs. 133,134

4.2 Plasma treatment

The effectiveness of plasma treatment in producing surface OVs on metal oxides has been well established. During plasma treatment, OVs 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 OVs across various materials for various purposes. 53,137,138 To demonstrate this phenomenon, OVs were induced on Co₃O₄ through a 2-minute treatment using Ar plasma (250 W) (Fig. 9a), 114 while H-doped black titania (TiO2@TiO2-xHx) enriched with OVs was achieved by subjecting it to H₂ plasma. 139 XPS analysis and EPR investigation provided confirmation of the presence of OVs in the samples subjected to plasma treatment (Fig. 9e and f).

Wet-chemical reduction

The wet chemical redox method offers a scalable solution for introducing OVs 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 oxygendefect peak, indicating a greater induction of oxygen defects in Bi₂O₃ after reduction. In a separate investigation, the induction of surface OVs in BiOIO3 was achieved by treating the sample with a KI solution under continuous stirring for 14 hours at room temperature 142 (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 OVs through

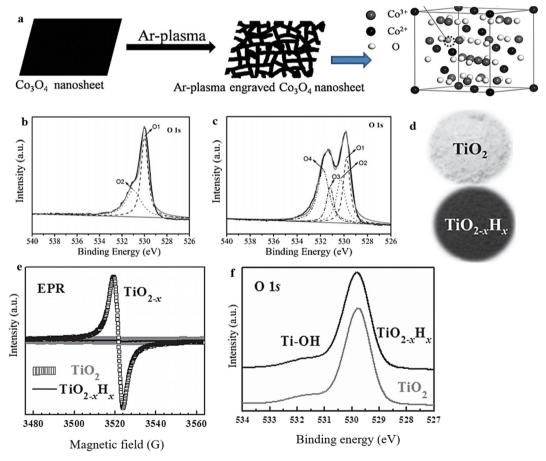


Fig. 9 (a) Illustration of the process for producing oxygen-vacancy-rich, high-surface-area Co₃O₄ that was etched using Ar-plasma. (b) and (c) XPS 1_S spectra of pristine Co₃O₄ and plasma-engraved Co₃O₄ respectively. Reproduced from ref. 114 with permission from Wiley, copyright 2016. (d) Photographs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

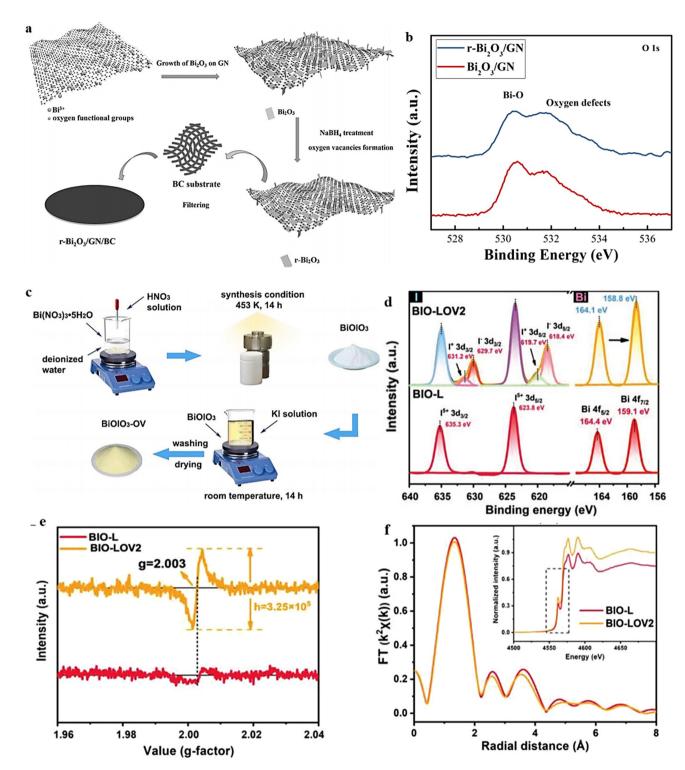


Fig. 10 (a) Schematic diagram showing the steps used to create a flexible $r-Bi_2O_3/GN/BC$ electrode during the synthesis process. (b) XPS analysis Bi-O. Reproduced from ref. 140 with permission from Wiley, copyright 2017. (c) Schematic illustration for the preparation process of BiOIO₃ and BiOIO₃-OV 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-LOV₂. Reproduced with permission. 142

XPS and EPR analyses. The presence of lower-valence iodine ions (I^+ 3d3/2, I^+ 3d5/2, I^+ 3d3/2, and I^- 3d5/2) in BiO-LOV₂ serves as evidence for the existence of OVs (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 I^{5+} 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 OVs in BIO-LOV₂. These OVs 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 OVs in the resultant material. Compared with the thermal protocol in an oxygendeficient condition, the hydrogenation procedure represents a simpler approach to generate OVs and transform different metal oxides (MOs) into their respective nonstoichiometric forms, as described in the following equation;

$$MO + \frac{x}{2}H_2 = MO_{1-x}(OH)_x$$

The generation of OVs 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 H_2 . This transformation was attributed to the formation of Ti^{3+} 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

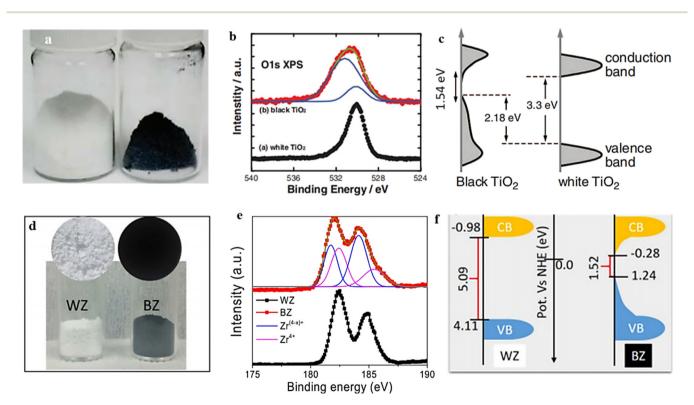


Fig. 11 (a) This image shows TiO2 nanocrystals in their natural white and disorder-engineered black nanocrystals. (b) TiO2 O 1s XPS spectra, both white and black. (c) Diagram comparing the DOS of disorder-engineered black TiO2 nanocrystals with that of unmodified black TiO2 nanocrystals. Reproduced from 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 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 Co(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 Co(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 Co(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 c). Wang and colleagues employed a straight-

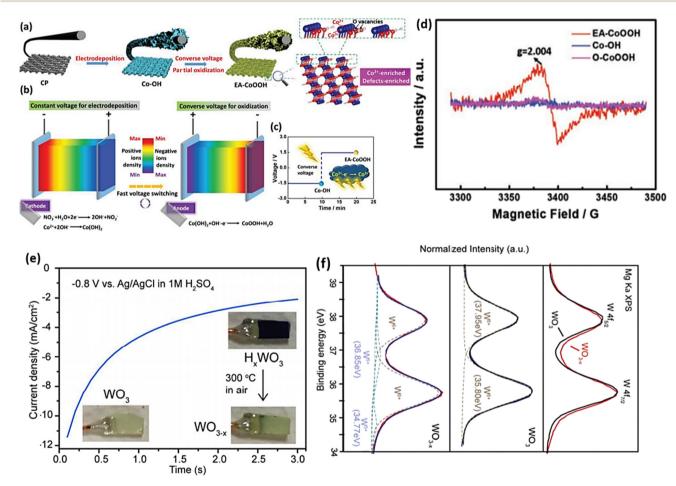


Fig. 12 (a) The molecular structure of EA-CoOOH exhibiting Co²⁺ and defect-enriched characteristics is shown schematically, and its synthesis through the converse voltage approach is also described. (b) Schematic representation of the process, showing a constant voltage used for electrodeposition and 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 M H₂SO₄ solution at -0.8 V vs. Ag/AgCl for 3 s, the cathodic current vs. time curve of the WO₃ film decreased. Inset: the electrochemical reduction of a light yellow WO₃ film results in a blue HxWO₃ film, which is then re-oxidized into WO_{3-x} when exposed to air. (f) Upper: WO₃ and WO_{3-x} XPS W 4f spectra after normalization. The synthetic peaks in the XPS W 4f spectrum of WO₃ that correspond to the W 4f5/2 and W 4f7/2 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 W⁶⁺ and W⁵⁺ (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 WO₃, TiO₂, ZnO and BiVO₄. 155 In this study, we use WO₃ 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 prisitine 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-WO₃ (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 Co₃O₄ nanoneedles on carbon cloth (Mo-Co₃O₄@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 Co³⁺/Co²⁺ 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 Co₃O₄, 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 *CO and *OCCO species (Fig. 13d).

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

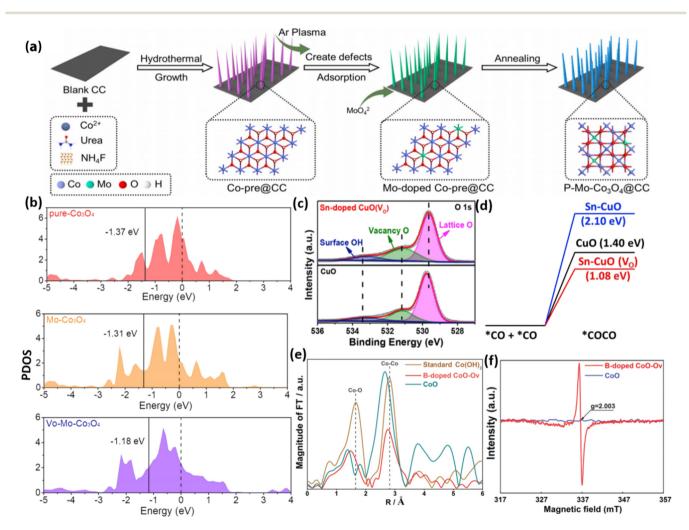


Fig. 13 (a) The figure provides a schematic depiction of the synthesis process for P-Mo-Co₃O₄@CC. (b) PDOS of pure-Co₃O₄, Mo-Co₃O₄, and V_O-Mo-Co₃O₄. Reproduced from ref. 53. (c) XPS O 1s spectra of CuO and CuO that have been doped with Sn (V_O). (d) Diagram illustrating the amount of energy required for CO dimerization (*CO + *CO *OCCO) on CuO (black), Sn-CuO (blue), and Sn-CuO(VO) (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 Co(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 OVs 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 OVs in the engineered material, as depicted in Fig. 13c. This was demonstrated by synthesizing CoO nanowires containing OVs by adding B using a straightforward pyrolysis technique. The evidence from EPR and XAS analysis supports the notion that the OVs 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 OVs 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 OVs in metal oxide catalysts, along with the corresponding techniques to detect OVs, 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 OVs, 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 OVs 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 OVs 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 OVs in a nanomaterial so does its electrochemical performance. Recognizing the significance of OVs in metal oxides, Jia et al.105 investigated the impact of OVs on the adsorption energy of NO₃⁻ on the TiO₂(101) surface by varying the number of OVs from zero to one and two in TiO_{2-x} . The OVs 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 OVs within the specified material. The electrochemical performance results revealed a notable decline in adsorption energy as the concentration of OVs 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 OVs 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 OVs 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 OVs (three OVs) in CuO lowered the adsorption energy, which in turn facilitated a noteworthy adsorption of NO₃⁻. The introduction of OVs 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 OVs increased, the adsorption energy significantly decreased to -1.84 eV (two OVs) and -2.08 eV (three OVs), as shown in Fig. 14i. These results suggested that an "adequate amount" of OVs 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 OVs) and -1.5 eV (Cu₂O), at -0.6 V vs. RHE. Furthermore, it was observed that introducing OVs 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 CuOx 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 OVs on the CuOx surface led to a decrease in electron density, reduction in surface crystallinity, and alteration in the surface chemical state.

Combining and forming OVs 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

Review

 Table 1
 Summary of commonly used approaches to construct OVs 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	47
Electrospinning, calcination	${\rm Fe_2TiO_5}$	Raman, XPS, EPR,	it was subjected to a plasma treatment for 5 and 10 minutes. 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 $^{\circ}$ C for 1 h and calcined at 650 $^{\circ}$ C for 3 h.	
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	$\mathrm{Cu_2O}$	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 Papressured vacuum chamber, with a radio frequency generator power of 200 W.	164
Elemental doping	${\rm Fe\text{-}TiO_2}$	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, $C_6H_8O_7$ (6 mmol) and $C_{10}H_{16}N_2O_8$ (4 mmol) were added as complexing agents. The pH of the mixed solution was adjusted to alkaline by addingNH 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	${ m TiO_2}$	XRD, XPS, UV-Vis DRS	${ m Ti(SO_4)_2}$ was reacted with ammonia water in an ice-water bath for 2 hours, and then ${ m TiO_2}$ was obtained after centrifuging, washing, and drying the solution at 80 °C. The produced ${ m TiO_2}$ was subjected to an ultrasonic treatment at 80 °C for varying times (0.5 h, 1 h,	166
Nano-crystallization	$\mathrm{Bi}_2\mathrm{O}_3$	HAADF STEM, XPS, ESR, PL	2 h, 4 h, and 8 h) with an output power density of 1500 W/100 mL. 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_2O_2 . While still stirring, 50 mL of deionized water and 10 mL of 100% ethanol were added to the aforementioned mixture. Then, $Ce(NO_3)_3$ · $6H_2O$ 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	${\rm Fe\text{-}TiO_2}$	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 In(NO ₃) ₃ ·4H ₂ 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 OVs in InOOH.	169
Self-assembly solvothermal method	$\mathrm{Bi}_{24}\mathrm{O}_{31}\mathrm{Br}_{10}$	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 NO₃RR compared with other electrochemical NH₃ synthesis routes^{238,242}

N_2 electrochemical reduction	NO electrochemical reduction	NO ₃ ⁻ electrochemical reduction
• The solubility challenge of the conventionally used inert N_2 has consequences for the generation of ammonia (NH $_3$) in aqueous environments.	\bullet The challenge of solubility in aqueous solutions directly impacts ammonia (NH $_{\! 3})$ production.	 Nitrate ions (NO₃⁻) have gained prominence as a significant nitrogen source in contrast to the conventionally inert N₂ for the electrochemical generation of NH₃, contributing to their widespread prevalence as water pollutants across the globe. The low bond dissociation energy in NO₃⁻ renders this molecule an appealing candidate for NH₃ synthesis.
\bullet The considerable energy needed to break the bonds in N_2 makes it economically unfeasible for the electrochemical production of $NH_3.$	• Environmental samples typically contain a low concentration of NO, necessitating an additional energy-intensive step to concentrate it for the electrochemical reaction.	
• 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.	• 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.	• A broad range of electrocatalysts have shown noteworthy improvements in both faradaic efficiency (FE) and yield rates.
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.	• 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.	 There is a significant disparity between the reaction potential of NO₃⁻ (0.69 V) and that of the hydrogen evolution reaction (HER). Therefore, the reduction of NO₃⁻ to NH₃ successfully circumvents the impediments posed by the hydrogen evolution reaction (HER). Lastly, the presence of NO₃⁻ 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 Fe₂TiO₅ 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_0) 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 Fe³⁺ ions to replace Ti⁴⁺ ions, thereby inducing the formation of oxygen vacancies. The density of states calculations have revealed that introducing OVs 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 Vo, which contributes to the catalyst's higher catalytic activity. The thermodynamic study indicates that the adsorption of the NO₃⁻ 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

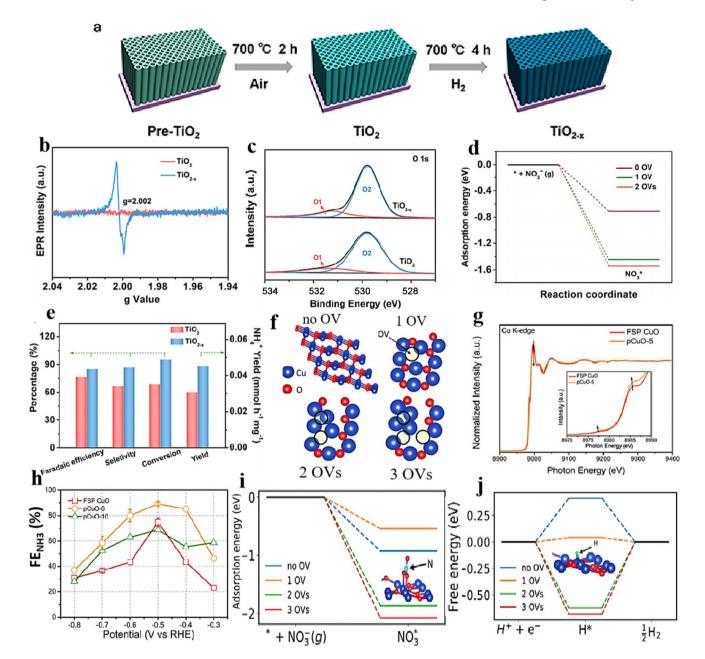


Fig. 14 (a) TiO_{2-x} synthesis diagram. (b) EPR spectral analysis. (c) TiO₂ and TiO_{2-x} XPS spectra. (d) Energy required for NO₃⁻ adsorption on TiO₂(101) surfaces with 0 OVs, 1 OVs, and 2 OVs. (e) TiO_{2-x} and TiO_2 were compared with respect to their NH⁴⁺ FE, selectivity, yield, and NO_3^- conversion rate. Reproduced from ref. 105 with permission from the American Chemical Society, copyright 2020. (f) Top view of the relaxed structures of the CuO (111) surface with 1, 2, and 3 OVs, with the missing oxygen atoms indicated by the circles in the pristine 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 FE_{NH4+} concentration on the applied potential for FSP CuO, pCuO-5, and pCuO-10 in 0.05 M KNO₃ and 0.05 M H₂SO₄. (i) NO₃⁻ adsorption energies on 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 NO₃ on pristine TiO₂ and TiO₂-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 NH₃ yield of 13.3 mg h⁻¹ mg_{cat}⁻¹. These values were further enhanced to

96.06% and 1.36 mmol h^{-1} mg_{cat}^{-1} at 0.9 V vs. RHE (Fig. 150). 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 V2O5 (resulting in Fe-V2O5) 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 OVs, and it

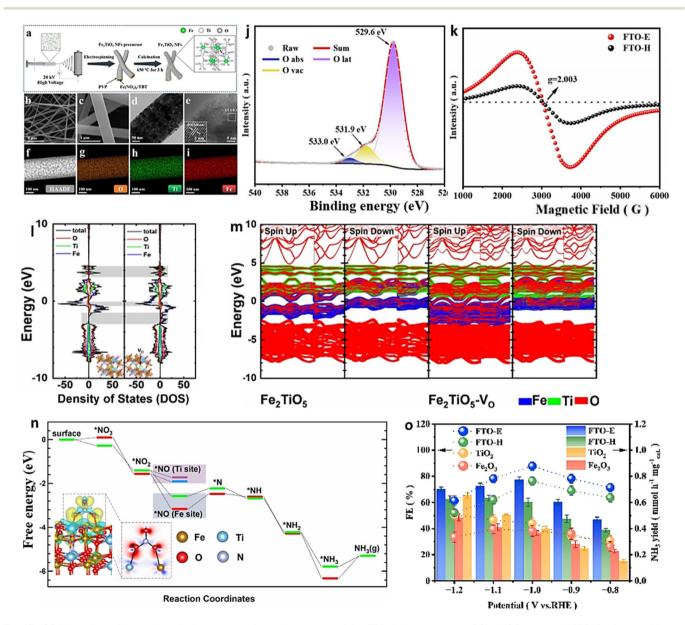


Fig. 15 (a) Illustration of the schematic for the manufacturing process of the FTO-E electrocatalyst. (b) and (c) Images of FTO-E taken at different SEM magnifications. (d) TEM analysis of FTO-E. (e) HR-TEM photo of FTO-E. (f) HAADF STEM image and EDX mapping of the O (g), Ti (h) and Fe (i) elements 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-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) Fe_2TiO_5 and Fe_2TiO_5 -VO free energies. The bottom left shows the NO_3^- 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 ($NH_2^* \rightarrow NH_3^*$). 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 Vo 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 μ mol·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 Vo 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 NH_3 yield of 56.2 mg h⁻¹ mg_{cat}⁻¹ for NH_3 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 sequestrating 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 ratelimiting step of *NO \rightarrow *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

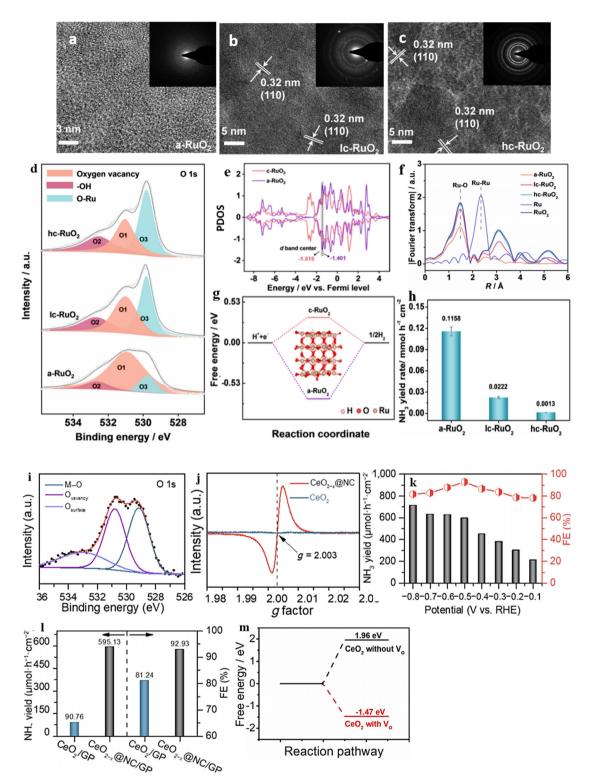


Fig. 16 HRTEM images of (a) a-RuO₂, (b) lc-RuO₂, and (c) hc-RuO₂. The insets in (a)–(c) are the corresponding SAED images. (d) O 1s XPS spectra of $a-RuO_2$, $lc-RuO_2$, and $hc-RuO_2$. (e) PDOS of d-bands for $a-RuO_2$ and $c-RuO_2$ and the corresponding d-band centers. (f) k^3 -Weighted Fourier-transformed 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 CeO_{2} . (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.

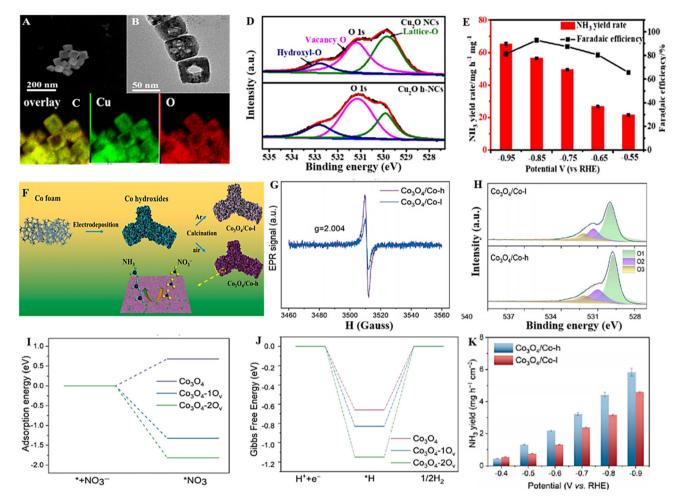


Fig. 17 (A) SEM, (B) TEM, and (C) EDX map images of Cu₂O h-NCs. (D) O 1s XPS spectra and (E) NH₃ yield and the corresponding FE of NO₃⁻ reduction to NH₃ on Cu₂O h-NCs. Reproduced from ref. 46 with permission from the American Chemical Society, copyright 2022. (F) A graphic photograph of the Co_3O_4 synthesis 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 H₂ generation. (K) NH₃ yield of Co₃O₄ samples at different potentials. Reproduced from ref. 183 with permission from Elsevier, copyright 2023.

sufficient oxygen vacancy defects on Co₃O₄ promotes energetically favorable NO₃ adsorption and enhances NO₃RR activity. In terms of the HER (Fig. 17J), the energy barrier required for hydrogen evolution is higher for Co₃O₄-2Ov (1.15 eV) compared with Co_3O_4 -1Ov (0.83 eV) and Co_3O_4 (0.66 eV). This implies that the HER on Co₃O₄-2Ov 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 Co₃O₄-2Ov sample (Fig. 17K).

Gong et al. conducted a study using an Ar plasma treatment method to produce Cu₂O with oxygen vacancies. XPS measurements were employed to analyze the oxygen analysis of both untreated and plasma-treated Cu₂O samples (Fig. 18a and b). The amount of OVs 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 Cu₂O exposed to plasma treatment (40 minutes) exhibited the highest activity in the NO₃RR, yielding an NH3 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 NO₃RR. Likewise, Cu₂O with one oxygen

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vacancy (Cu₂O with OV) on the (111) surface shows a significant reduction in the adsorption energy of NO₃⁻ (-2.25 eV) compared with the pristine Cu₂O surface (-0.97 eV). This trend is also observed for other reaction intermediates, which display lower adsorption energies on Cu2O with OV than on the pristine surface. The enhanced performance of the defective Cu₂O can be attributed to the combination of an increased charge density, upshift of the d-orbital, and reduced adsorption energies of NO₃ and other reaction intermediates. Cu/ TiO₂ hybrid catalyst was prepared by Zhang and their team, ¹⁰⁶ which involved the uniform dispersion of Cu clusters on TiO₂ 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 NO₃RR (Fig. 18k). Bader analysis demonstrated that the transfer of 1.47 and 1.39 electrons occurred from Cu clusters to TiO2 and TiO2-x, respectively. Consequently, the Cu/TiO₂ functioned as a donor-acceptor pair, thereby promoting the absorption/separation of NO₃⁻ and the desorption of NH_3 . The hybrid catalyst $10Cu/TiO_{2-x}$ was able to significantly enhance the performance of ammonia synthesis, yielding a faradaic efficiency of 81.34% and a rate of NH3 production of $0.1143 \text{ mmol h}^{-1} \text{ mg}^{-1}$ at a voltage of -0.75 V (Fig. 181).

In a recent study, Wang and colleagues¹⁶⁵ introduced Fe atoms to TiO2 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 FeTiO2 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 Fe-TiO₂-V_{O1}, Fe-TiO₂-V_{O2}, and Fe-TiO2-VO3 were decreased to 1.85, 1.87, and 1.84, respectively, all of which were lower than that of pristine TiO₂ (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 Fe-TiO₂-V_{O3} material was the most stable structure with induced defects for both NO₃⁻ adsorption and subsequent reduction among the prepared materials (Fig. 19g). In addition, Fe-TiO₂-V_{O3} demonstrated a higher energy barrier for competitive H2 generation (1.44 eV) than pristine TiO₂ (-0.46 eV), indicating a stronger suppression of H₂ 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 H₂ production in Fe-TiO₂ promotes a high faradaic efficiency. As a result, Fe-doped TiO2 demonstrated enhanced catalytic performance in the NO₃RR. Fe-TiO₂ exhibited a sig-

nificantly improved electrocatalytic performance in nitrate reduction, with an ammonia yield rate of 137.3 mg h⁻¹ mg_{cat} .⁻¹ and a faradaic efficiency of 92.3% at -1.4 V (vs. RHE), as compared with pristine TiO2 (which had an ammonia yield rate of 28.8 mg h⁻¹ mg_{cat}.⁻¹ and a faradaic efficiency of 54.7%).

ZnCr₂O₄ nanofiber, a zinc-rich spinel, was synthesized by Dong et al. 188 and used as a high-performance NO₃RR electrocatalyst for ambient NH3 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 NH3 yield rate of 20.36 mg h^{-1} mg_{cat.}⁻¹ and an FE of 90.21% at -1.2 V vs. RHE. According to theoretical calculations, ZnCr₂O₄ 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 Vo results in the creation of more antibonding states. 189 Moreover, the Zn-rich surface of the ZnCr₂O₄ catalyst facilitates the transfer of electrons from the metal active site, resulting in the efficient reduction of NO₃⁻ to NH₃.

Due to its cost-effectiveness and eco-friendliness, manganese oxide has demonstrated promising performance in various electrochemical reactions, including the NO₃RR. 190,191 Likewise, Cu-based materials have exhibited significant outcomes in the electrochemical reduction of NO₃⁻ to NH₃. ^{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 MnCuOx 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 MnCuOx-H indicates a larger quantity of OVs following plasma irradiation. The MnCuO_x catalyst with a high concentration of OVs (MnCuO_x-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 NO₃ and a weakening of the N-O bond, leading to a superior performance. Similarly, a dual-site electrocatalyst for NO3- reduction was developed by Wang et al. 195 which was composed of MnO₂-O_v nanosheets enriched with OVs, and Pd nanoparticles that were deposited onto 3D porous nickel foam (Pd-MnO₂-O_v/ Ni foam). XPS and EPR spectral studies revealed the presence of OVs. The Pd-MnO₂-O_v/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 NO₃ and other intermediates through the MnO₂-O_v nanosheets, while the Pd provided sufficient adsorbed hydrogen (H*) to the oxygen vacancy sites for both NO₃ reduction and OV regeneration, as evidenced by experi-

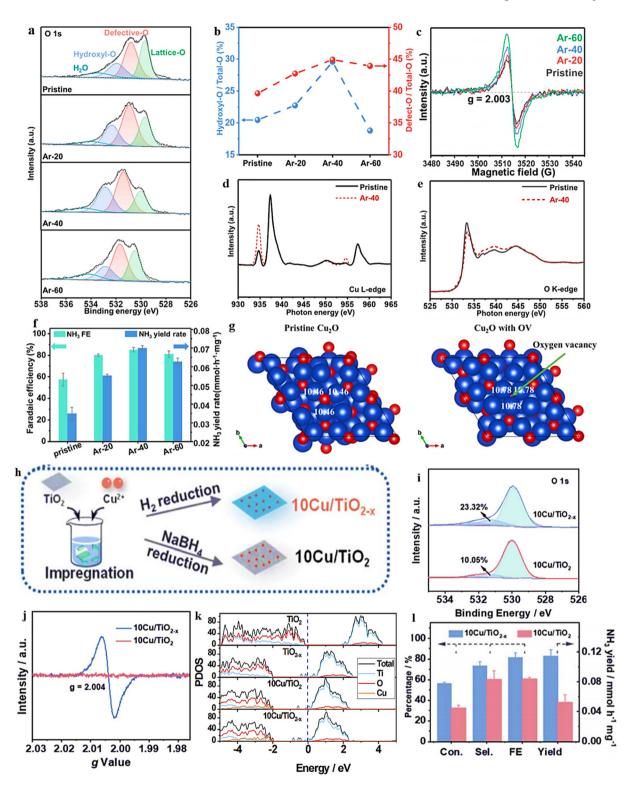


Fig. 18 (a) O 1s XPS spectra of pristine, Ar-20, Ar-40, and Ar-60. (b) The proportion of pristine, Ar-20, Ar-40, and Ar-60 areas that are occupied by O species. (c) The pure Ar-20, Ar-40, and Ar-60 EPR spectra. (d and e) X-ray absorption spectra (XAS) of pure Cu L-edge and Ar-40. (f) Ammonia production 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 $10Cu/TiO_2$ for NO_3^- 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.

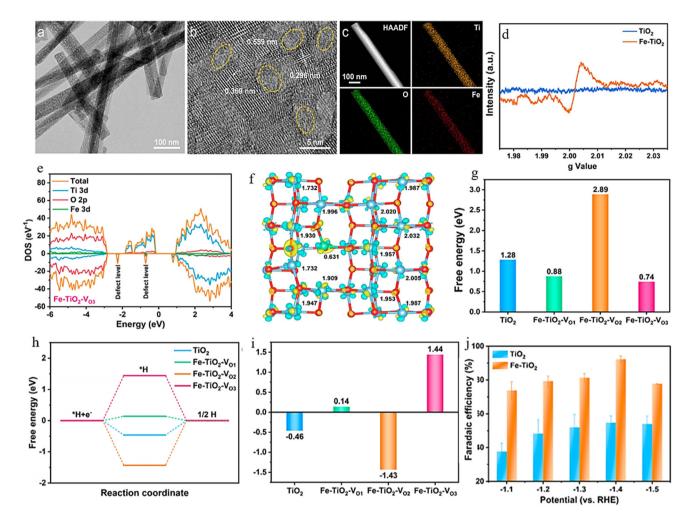


Fig. 19 Morphological and ex situ characterization: (a) TEM image. (b) HR-TEM observation (areas with yellow dots have morphological irregularities), (c) HAADF-STEM and EDS mapping of Fe-TiO2 images. (d) The TiO2 and Fe-TiO3 spectral analysis by EPR. (e) DOS of Fe 3d, Ti 3d, and O 2p of the compound Fe-TiO₂-VO₃. (f) The Bader charge values of the surface Ti atoms in the hybrid Fe-TiO₂-VO₃. The level of the isosurface is between 0.05 and 0.05 e Bohr⁻³. (g) The RDS of the NO₃RR over pure TiO₂ and Fe-doped TiO₂ is expressed in terms of Gibbs free energies. (h) Hydrogen evolution process over pure TiO₂ and Fe-doped TiO₂ – free energy diagrams. (i) The Gibbs free energies for the RDS of the HER over pristine TiO₂ and Fe-doped TiO₂ samples. (j) Efficiency of ammonia formation by faradaic reactions on TiO₂ and Fe-TiO₂ at various potentials. Reproduced from ref. 165 with permission from the American Chemical Society, copyright 2023.

mental characterizations and theoretical calculations (Fig. 20h). Palladium (Pd) has also been documented to synergistically trigger the activation of NO₃⁻ and disrupt *NO on the Bi1Pd catalyst. This results in a lowered energy barrier for the potential-determining step (NO -> NOH) and improved protonation dynamics along the NO₃⁻-to-NH₃ pathway. ¹⁹⁶ In another study, Wang and colleagues¹⁹⁷ were able to successfully create a new type of material, namely Cu/Cu-Mn₃O₄ NSAs/ CF (Fig. 20i), which contained a significant number of interfaces between Cu and Cu-Mn₃O₄, as well as a high concentration of OVs. This material exhibited exceptional electrocatalytic activity in converting nitrate to ammonia, obtaining remarkable results in terms of NO₃⁻ conversion (95.8%), NH₃ selectivity (87.6%), NH₃ production rate (0.21 mmol h⁻¹ cm⁻²), and FE (92.4%) when an applied potential of -1.3 V (vs. SCE) was applied. XPS and EPR investigations revealed a higher abundance of oxygen vacancies in Cu/Cu-Mn₃O₄ compared with the Mn₃O₄ NSs sample (Fig. 20l and m). The superior electrocatalytic performance of the material was attributed to the combined effects of the numerous Cu/Cu-Mn₃O₄ interfaces and the abundance of OVs, which together assisted in the modification of the surface electrical structure, allowing for the adsorption and activation of NO₃⁻ (Fig. 200).

Meng and colleagues 198 utilized a novel method to generate ammonia using a Co₂O₃ catalyst that contained multiple OVs. The catalyst was synthesized using a precipitation technique (Fig. 21a), and the OVs were identified through XPS analysis (as shown in Fig. 21b and c). The NH₃ synthesis was accomplished by combining non-thermal plasma oxidation and electroreduction (Fig. 21d). To initiate plasma activation of air in the first step, a Ti bubbler was introduced, resulting in the effective production of nitrate/nitrite (NO_x⁻) in an absorption

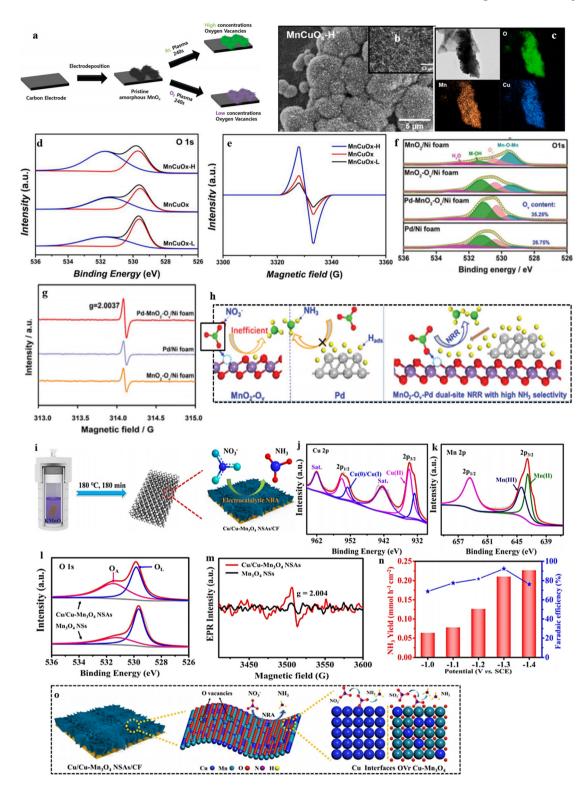


Fig. 20 (a) Illustration in the form of a schematic showing the complete synthesis process for MnCuO_x catalysts. (b) SEM morphology of MnCuO_x-H. (c) The elemental distribution of oxygen, manganese, copper, and their overlay in a selected area of MnCuO_x-H, as shown by EDX. (d and e) The XPS spectra 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 PdMnO₂ sample and (h) a schematic of the high-NH₃ selectivity MnO₂-Ov-Pd dual-site NRR mechanism. Reproduced with permission. 195 (i) Electrocatalytic NO_3^- reduction by $Cu/Cu-Mn_3O_4$ NSAs/CF: a preparation and illustration scheme. (j–l) XPS spectra of distinct Cu2p, Mn 2p, and O 1s orbitals in various Cu/Cu-Mn₃O₄ samples. (m) EPR of Cu/Cu-Mn₃O₄ samples. (n) Production of NH₃ and FE at different potentials. (o) A schematic representation of the electrocatalytic reduction of NO₃⁻ to NH₃ conversion on Cu/Cu-Mn₃O₄ 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 ΔG 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 colleagues 199 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 $Cu-Co_3O_{4-x}$.

Similarly, $Cu-Co_3O_{4-x}$ 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. 210). 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 ABO₂-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

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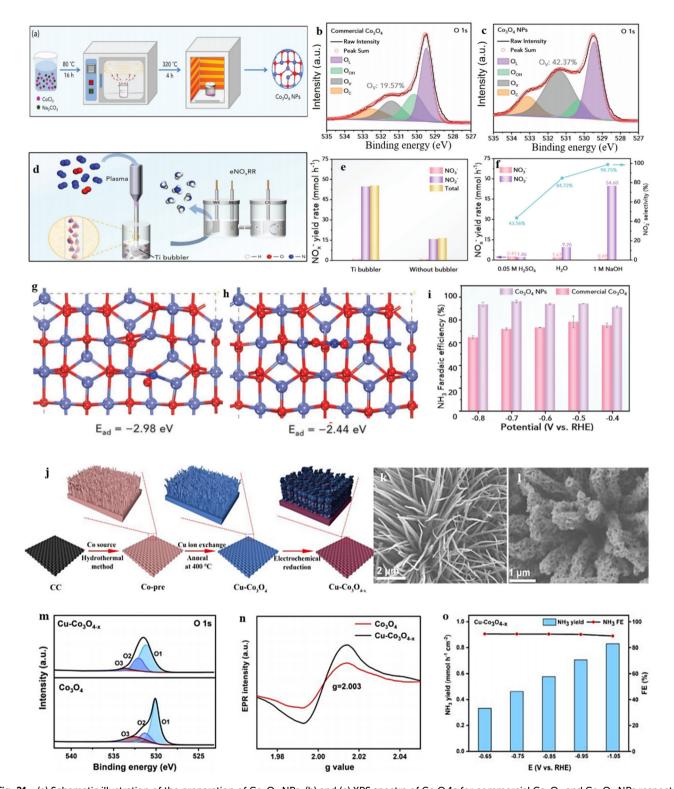


Fig. 21 (a) Schematic illustration of the preparation of Co₃O₄ NPs. (b) and (c) XPS spectra of Co O 1s for commercial Co₃O₄ and Co₃O₄ NPs respectively. (d) Complete system of N_2 fixation to NH_3 . (e) NO_x^- yield rate with and without a Ti bubbler in NaOH (1 M) absorption solution after 10 min plasma 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 $_3$ O $_4$ and (h) Co $_3$ O $_4$. (i) NH $_3$ FEs. Reproduced from ref. 198 with permission from Wiley, copyright 2023. (j) Schematic illustration of the synthesis process for $Cu-Co_3O_{4-x}$ on carbon cloth. (k) and (l) SEM images of $Cu-Co_3O_4$, and Cu-Co₃O_{4-x} respectively. (m) and (n) XPS spectra of O 1s and EPR spectra of Co₃O₄ and Cu-Co₃O_{4-x}. (o) NH₃ yield rate and FE of Cu-Co₃O_{4-x}. Reproduced from ref. 199 with permission from RSC, copyright 2023.

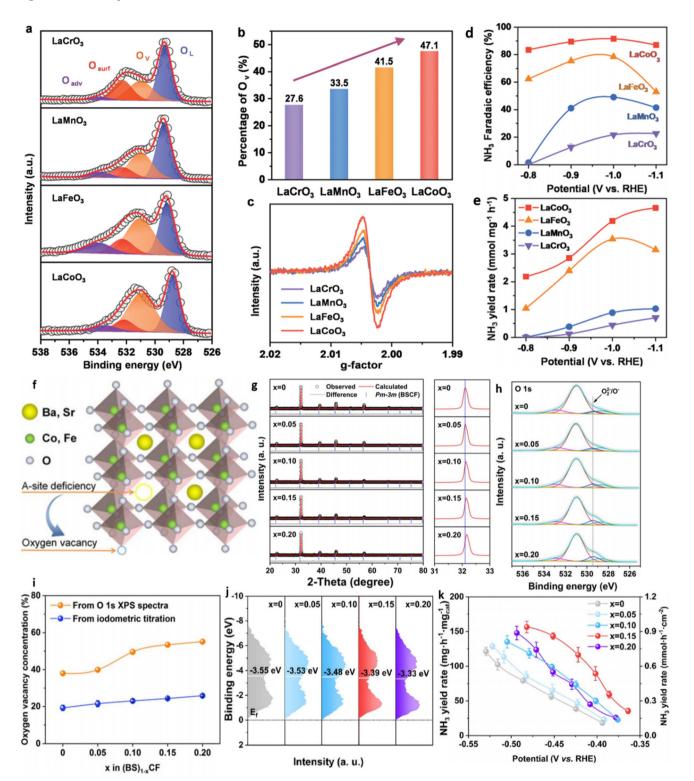


Fig. 22 (a) LaCrO₃, LaMnO₃, LaFeO₃, and LaCoO₃ O 1s spectra with high resolution by XPS analysis. (b) The percentage of oxygen vacancies for LaCrO₃, LaMnO₃, LaFeO₃, and LaCoO₃ from XPS analysis. (c) EPR spectra of LaCrO₃, LaMnO₃, LaFeO₃, and LaCoO₃. (d) NH₃ FE at different potentials, and (e) NH₃ yield 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)_{1x}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)_{1x}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 NO₃ER catalysis. Among them, the (BS)0.85CF catalyst exhibited the highest activity $(143.3 \text{ mg h}^{-1} \text{ mg}_{cat}^{-1} \text{ or } 0.86 \text{ mmol h}^{-1} \text{ cm}^{-2})$ 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 NO₃ER 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 inplane heterostructured nanosheet structure, Cu/CuOx/CF, characterized by a high abundance of OVs (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 OVs 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 NO₃-to-NH₃ conversion. Notably, the NH₃ yield rate on Cu/CuO_x/CF can achieve 0.23 mmol h⁻¹ cm⁻² at −1.3 V (vs. SCE), with an excellent NO₃ conversion efficiency (99.52%), NH₃ selectivity (95.00%), and NH₃ faradaic efficiency (FE, 93.58%) (Fig. 23g, h, and i).

Tungsten (W) catalysts having OVs are extensively utilized to enhance selective NH₃ synthesis. For instance, WO_{3-x} nanosheets and WO3-x nanowires with OVs can influence the adsorption of N species and mitigate the competing HER to some degree.213 Consequently, it is expected that OVs 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 OVs 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 NO₃⁻ on NbWO_{6-x} (-1.27 eV) is significantly lower compared with NbWO6 (-0.53 eV), making it more favorable for NO₃⁻ adsorption (Fig. 24f). This enhanced adsorption capability facilitates nitrate reduction to NH₃.

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 NH₃ 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 OVs for nitrate reduction to produce NH3. The XPS spectra of Nb_2O_5 exhibit a single peak at 530.5 eV, whereas NbO_x displays an additional peak at 531.8 eV, suggesting the presence of OVs in the NbO_x sample (Fig. 24h).⁵⁷ Furthermore, the investigation conducted by Pl demonstrated that the NbOx sample contains a higher concentration of OVs compared with the Nb₂O₅ counterpart (Fig. 24i). The OV-rich material demonstrated an impressive faradaic efficiency (FE) of 94.5% and achieved an NH₃ formation rate of 55.0 μ g h⁻¹ mg_{cat}⁻¹ (Fig. 24j and k). A detail investigation revealed that the presence of OVs 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 OVs 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 NO₃ (Fig. 25g). The combined impact of these two factors is responsible for the exceptional NO₃ 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 electrochemical catalysis, the synergistic interaction between these two species has received limited attention.

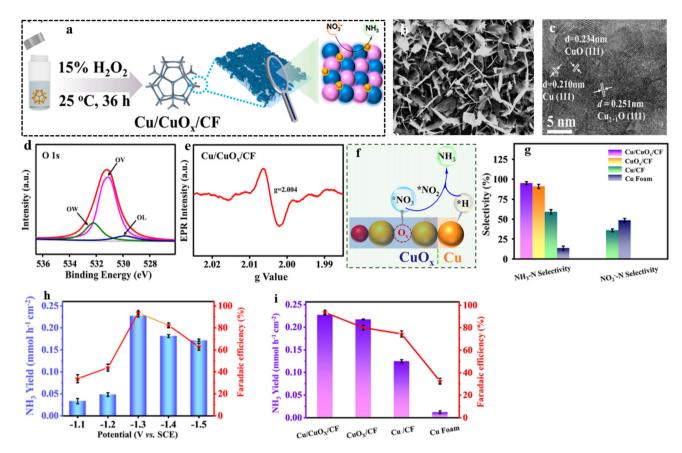


Fig. 23 (a) A schematic depicting the production of $Cu/CuO_x/CF$ as well as its subsequent electroreduction using NO_3^- . (b and c) Images of $Cu/CuO_x/CF$ as well as its subsequent electroreduction using NO_3^- . CuO_x/CF were obtained using SEM and HRTEM. XPS spectra of O 1s as item (d). (e) EPR spectra. (f) A schematic representation of the electrochemical reaction that converts NO_3^- to NH_3 , which is catalyzed by the $Cu/CuO_x/CF$ system. Selectivity of the NH_3-N and NO_2-N , yield rate, and the FE of NH₃ for various samples (q-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 finetune 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 (NO_3^-) 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 Hads and NOads leads to their hydrogenation and the formation of various hydrogenated

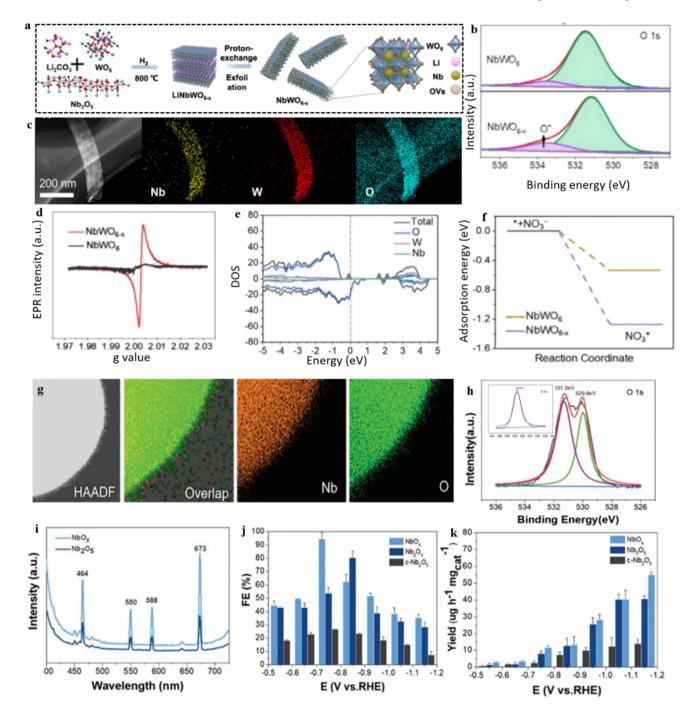


Fig. 24 (a) Schematic illustration of the NbWO $_{6-x}$ nanosheet synthesis. (b) O 1s XPS spectra. (c) The HAADF-STEM picture of the NbWO $_{6-x}$ nanosheets and their elemental mapping of Nb, W, and O. (d) EPR spectra, (e) The DOS diagram of NbWO_{6-x} and (f) calculated adsorption energies of NO₃⁻ on NbWO₆ 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 Nb₂O₅ (inset). (i) PL spectra of NbO_x and Nb₂O₅. (j and k) Faradaic efficiency and NH₃ yield rates at different potentials. Reproduced from ref. 217 with permission from RSC, copyright 2022.

intermediates, ultimately resulting in NH3 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 NO₃⁻.²⁰ The specific reaction conditions such as pH, concentration, and applied potential can influence the in situ reaction mechanism of electrochemical reduction of NO₃⁻. For instance, under acidic conditions, NH₃

production increases while NO2 decreases. In alkaline conditions, the main product is observed as NH₂OH, but NO₂⁻ also appeared as well, indicating that the pathway can be pHdependent.²³¹ Further studies, such as FTIR, have been conducted to investigate the detailed mechanism of NO₃reduction in the Cu(100) and Cu(111) facets in the presence of alkaline and acidic conditions. Likewise, the recent DFT

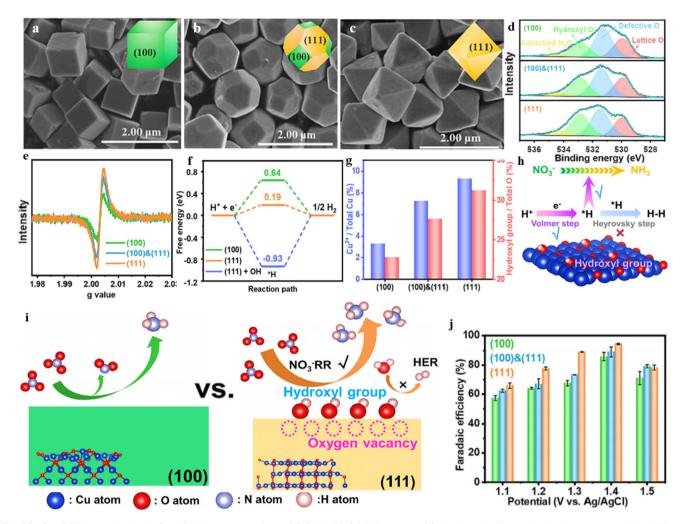


Fig. 25 (a-c) SEM morphologies (inset) of the exposed facet. (d) O 1s XPS. (e) EPR spectra. (f) A schematic illustrating the free energy of the HER as estimated by the DFT computation. (g) The percentage of Cu^{2+} , which is shown on the left side of the y-axis, and the hydroxyl group, which is shown on the right side of the y-axis, on the surface of Cu₂O(100), Cu₂O(100) and (111), and Cu₂O(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.

analyses32,233 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 NO_2^- , HNO_2 , NO_3 , and the final product NH_3 (Fig. 27e). Transition metals have also been found to form NOHads 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 NOads undergoes watermediated 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 NOads 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

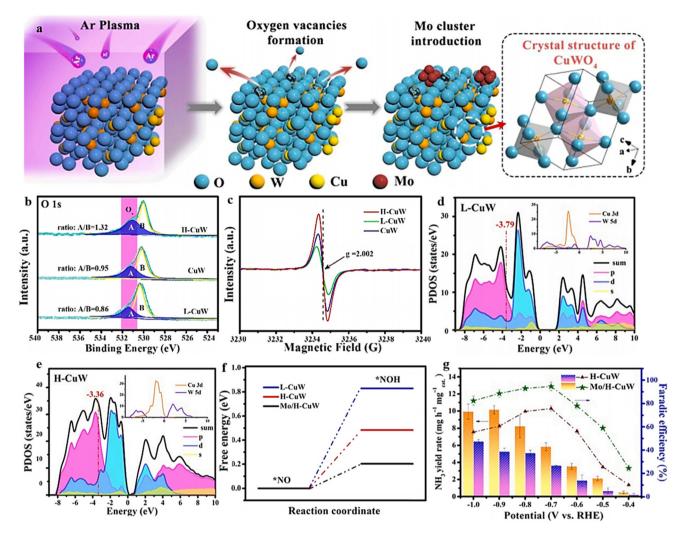


Fig. 26 (a) A diagrammatic representation of the steps involved in the Mo/H-CuW fabrication process. (b) and (c) show the XPS O 1s and EPR spectra of various materials. (d) PDOS of L-CuW and (e) PDOS of H-CuW, respectively. (f) A comparison of the changes in the Gibbs free energy that takes place during 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 NO₃⁻. In the study of Jia et al. 105 OVs were introduced into TiO2 to unveil the reaction mechanism for the selective generation of NH3. Different models of TiO₂(101) surfaces were considered, including those with single OVs, two OVs, and without OVs. The density of states (DOS) analysis indicates that TiO2(101) without OVs exhibited semiconductor behavior. However, the introduction of OVs 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 OVs, giving rise to the metallic characteristic of TiO2-x and improving the conductivity. This improved conductivity is beneficial for the electrochemical reduction reaction. The adsorption energy of NO₃ on the surface of TiO2(101) was investigated for different configurations. It was found that TiO₂(101) with a single inserted OV (-1.44 eV) or two OVs (-1.54 eV) showed much higher adsorption energy as compared with TiO2(101) without OVs (-0.71 eV) (Fig. 27i). This indicates a stronger binding of NO₃⁻

on TiO2 surfaces with OVs. The reaction Gibbs free energy (ΔG) of NO₃ was calculated for different configurations.

In the case of NO₃⁻ adsorption on the surface of TiO₂(101) in the absence of OV, as shown in (Fig. 27j), the NO₃ O1 makes bond-coordination via unsaturated Ti, while O2 and O3 are shown exposed to the ambient reaction environment. The NO₃* is hydrogenated and formed HNO₃*, 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 HNO3* leaves H to form NO2* and a water molecule. NO2* is automatically transformed to make NO₂ or HNO₂, thus further hindering the reduction of NO₂*. Considering TiO₂(101) with the insertion of a single OV, the O1 of the NO₃* 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,

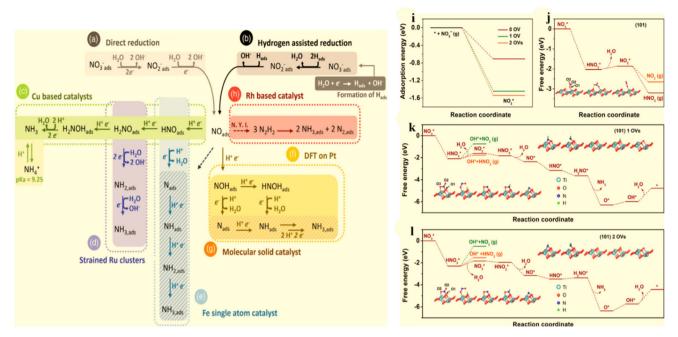


Fig. 27 (a-h) Proposed reaction pathways for ammonia synthesis reported by various latest literature reports. 241 (i) Nitrate adsorption energies on the surface of TiO₂(101) via zero, one and two OVs, (j) without OVs, (k) with one OV, and (l) two OVs at 0 V vs. RHE. 105 With permission from the American 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. 61), 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 oxygennitrogen 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

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 OHspecies 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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