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Hydrogen-bond mediated electrocatalytic nitrate reduction to ammonia over metal–organic frameworks with industrial current density†

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Electrocatalytic reduction of the pollutant nitrate to ammonia (NO₃RR) using clean energy is being considered as a viable alternative to the Haber–Bosch process for producing industrially valuable ammonia. However, the multi-electron–proton transfer process of the NO₃RR to ammonia usually leads to poor selectivity and low current density, which still cannot meet the industrial requirements. Stabilizing the key intermediates during the reaction is particularly important for achieving high selectivity in the NO₃RR towards the production of NH₃. Herein, we develop a hydrogen bonding strategy to stabilize the key intermediates of the NO₃RR, which involves the design and synthesis of trinuclear copper(i) cluster-based metal–organic frameworks (MOFs). The methyl groups in the copper-based MOFs (DiMe–Cu₃–MOF) can regulate the electron density around the Cu₃ site and stabilize the key intermediates, *NO₂, through hydrogen bonding interaction with methyl groups. Thus, the DiMe–Cu₃–MOF electrocatalyst delivers a high NH₃ faradaic efficiency (95%) for the NO₃RR with a high ammonia production of 401 μg cm^{−2} h^{−1}, and the partial current density of ammonia reaches an industrial level value of −950.6 mA cm^{−2}. Control experiments and theoretical studies demonstrated that the introduction of methyl groups into the DiMe–Cu₃–MOF can facilitate atypical hydrogen bonding with the intermediates of the NO₃RR and thus enhance the adsorption of intermediates and reduce the energy barrier of the conversion of NO₃[−] to NH₃. This work highlights the vital importance of adjusting the microenvironment through hydrogen bonding for enhancing the NO₃RR performance.

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Introduction

The removal of pollutants from aqueous solutions and the production of high-value compounds through green recycling are crucial for establishing a sustainable society with efficient resource recycling.^{1,2} Nitrates, originating from the long-term and continuous application of organic or synthetic fertilizers, pose a significant threat to groundwater and affect most aquifers in agricultural regions.³ Furthermore, excessive nitrate accumulation in the human body can be converted into carcinogenic *N*-nitroso substances, leading to serious diseases like methemoglobinemia.^{4,5} Physical methods such as electrodialysis, reverse osmosis, and membrane filtration techniques have

been employed to separate nitrates from domestic sewage, inorganic fertilizers, nitrified soil organic matter and so on.⁶ Compared with physical approaches, the catalytic transformation of nitrate into useful chemicals such as ammonia not only promotes denitrification of wastewater and balances the disrupted nitrogen cycle, but also has the potential to become a promising pathway for renewable ammonia production.^{7,8} As is well known, the industrially important ammonia is conventionally produced using the Haber–Bosch process, which involves the mixing of hydrogen and nitrogen at high temperatures ranging from 400 to 650 °C and pressurizing them to 200 atm.⁹ In addition to the stringent conditions of high temperature and high pressure required to break the N≡N bond, the production and purification of H₂ constitute the first step, which consumes a large amount of fossil fuels and results in energy waste and environmental pollution.¹⁰ Therefore, there is an urgent need for a clean, efficient, and sustainable ammonia production method to replace the energy-intensive and highly polluting Haber–Bosch process.¹¹ An electrochemical reduction method using clean energy to convert toxic nitrates into ammonia offers a sustainable alternative to replace the Haber–Bosch process.¹² The electrocatalytic process of nitrate can be performed under ambient conditions, owing to the

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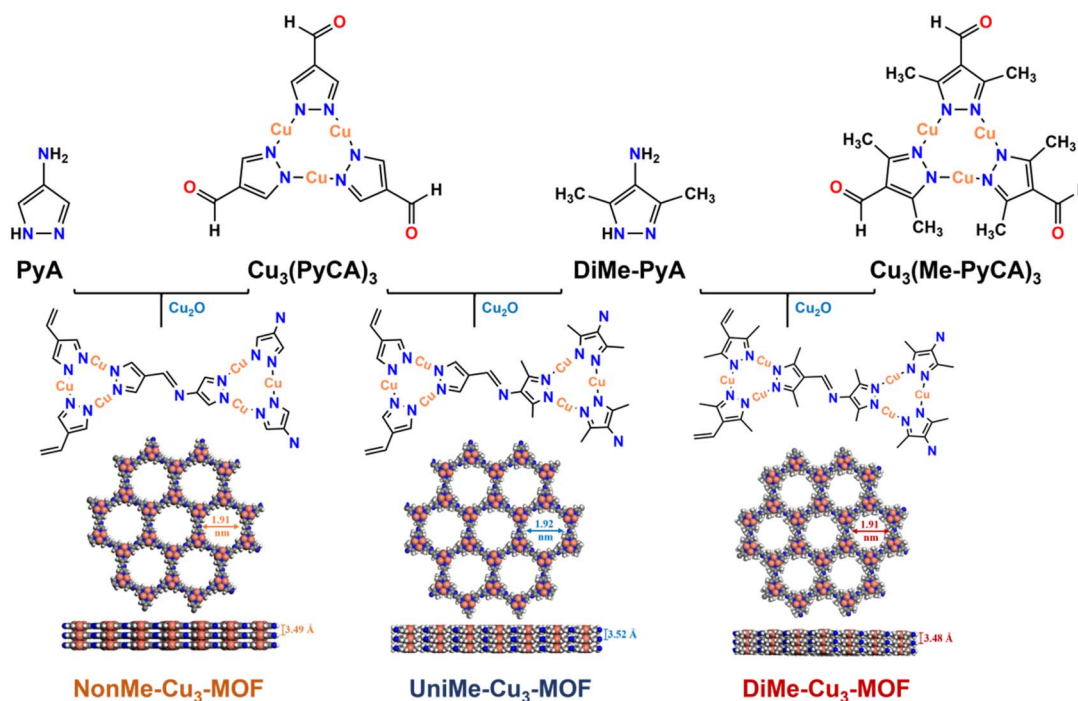
comparatively low bond energy of N–O (204 kJ mol^{-1}), thereby bypassing the energy-intensive N_2 cleavage step (941 kJ mol^{-1}) in N_2 electroreduction.¹³ In this context, the electrochemical nitrate reduction reaction (NO_3RR) represents a sustainable pathway to achieve carbon-free ammonia production, which can address water pollution issues and balance the nitrogen cycle.^{14–17}

The competing hydrogen evolution reaction (HER) usually occurs during the NO_3RR in aqueous electrolytes.¹⁸ Moreover, despite the lower activation energy barrier of N–O, the complex reaction pathway of the NO_3RR ($\text{NO}_3^- + 9\text{H}^+ + 8\text{e}^- \rightarrow \text{NH}_3 + 3\text{H}_2\text{O}$) involves multiple electron and proton transfers and production of several intermediates, which frequently results in low activity and selectivity of the NO_3RR , thereby posing a significant challenge for practical applications.^{19,20} Several electrocatalysts including metal-based electrocatalysts have been applied in the NO_3RR ; however, their activity and selectivity still need to be improved to meet the industrial requirements for ammonia production.^{21,22} Compared to other electrocatalysts, copper-based materials have been widely used in electrochemical reactions such as CO_2 reduction and the NO_3RR due to their suitable adsorption energy for intermediates.^{22–24} However, the various intermediates are usually detached from the copper active sites prior to completing the eight-electron transfer process required for ammonia generation.^{8,25} This is due to potential-dependent phase transitions, resulting in deactivation caused by changes in the oxidation state, morphology, crystal facets, and other factors. In addition, the process of reducing nitrate to ammonia involves eight electron transfer steps, and there may be multiple potential intermediates generated in the process, such as NO_2^- , NO , N_2 and NH_2OH .^{26,27} Therefore, stabilizing these

intermediates in the reaction process to prevent them from dissociating from the active site will be beneficial for the formation of the final product.

As is well known, regulating the microenvironments and introducing suitable groups into electrode materials could reduce the energy barrier of the electrochemical reaction and thus enhance the faradaic efficiency (FE) and selectivity.²⁸ Interestingly, the catalytic mechanism of one of the enzymes, copper nitrite reductase (CuNiR), involved in the biological reduction of NO_x to ammonia, involves the binding of NO_2^- to the catalytic center T2Cu, replacing a soluble molecule.²⁹ Simultaneously, hydrogen bonding forms between the residue coordinating with T2Cu and NO_2^- , leading to the formation of the subsequent intermediate in the reaction process.^{30,31} Inspired by this, introducing molecular interactions involving hydrogen bonding into the electrocatalytic NO_3RR can effectively stabilize specific intermediates and direct the reaction along the expected pathway.³² Currently, there is limited research on the precise control of electrocatalytic processes through weak interactions, such as hydrogen bonding. Therefore, it is necessary to develop new catalysts to enhance the NO_3RR .

Metal–organic frameworks (MOFs) have recently emerged as a promising class of crystalline porous polymers due to their large surface area, stability, and potential in various applications such as gas adsorption, heterogeneous catalysis, optoelectronic properties, and energy storage.^{33–36} The unique feature of flexible and designable structure endows MOFs be easily modified the microenvironment of the metal active sites through introducing functional groups. Thus, the hydrogen bonding interaction between the intermediates of the NO_3RR process with the introduced functional groups could be formed.



Scheme 1 Schematic diagram of the syntheses of NonMe- Cu_3 -MOF, UniMe- Cu_3 -MOF, and DiMe- Cu_3 -MOF.



Consequently, the selectivity of the NO₃RR towards the target products could be improved by reducing the reaction energy barrier. However, to the best of our knowledge, there is no report of using the hydrogen bonding strategy to enhance the NO₃RR performance.

Based on this, three examples of copper(i) cyclic trinuclear unit (Cu-CTU)-based two-dimensional (2D) MOFs were designed and synthesized to investigate how the structure of the catalyst affects the microenvironment of the copper active center during the nitrate reduction process.³⁷ As shown in Scheme 1, the DiMe-Cu₃-MOF was synthesized by the reaction of the copper(i) cyclic trinuclear cluster Cu₃(Me-PyCA)₃ (Me-PyCA = 3,5-dimethyl-1H-pyrazole-4-carbaldehyde), 3,5-dimethyl-1H-pyrazol-4-amine (DiMe-PyA)^{35,38} and Cu₂O. The copper center in DiMe-Cu₃-MOF is surrounded by two methyl (–CH₃) groups. Atypical hydrogen bonds C–H...Y (where Y is usually N and O) between the –CH₃ groups and the nitrogen-oxygen intermediates adsorbed on the copper center during the NO₃RR process may be formed. Thus, the intermediates could be stabilized and the energy barrier for ammonia generation would be lowered. For comparison, UniMe-Cu₃-MOF was prepared by the reaction of the methyl-free copper(i) cyclic trinuclear cluster Cu₃(PyCA)₃,³⁹ DiMe-PyA and Cu₂O. The NonMe-Cu₃-MOF containing no methyl group was also synthesized by imine condensation between Cu₃(PyCA)₃ and an amino copper(i) cyclic trinuclear complex, *in situ* generated from Cu₂O and 1H-pyrazol-4-amine (PyA). The activity of DiMe-Cu₃-MOF with atypical hydrogen bonds was higher than that of UniMe-Cu₃-MOF and NonMe-Cu₃-MOF, with the trend of DiMe-Cu₃-MOF > UniMe-Cu₃-MOF > NonMe-Cu₃-MOF. It is worth noting that DiMe-Cu₃-MOF exhibited a high faradaic efficiency (FE_{NH₃}) of

95% and achieved a high NH₃ partial current density (*j*_{NH₃}) of –950.6 mA cm^{–2}.

Results and discussion

As shown in Scheme 1, DiMe-Cu₃-MOF, in which all the Cu centers were surrounded by methyl groups, was successfully synthesized by reacting Cu₃(Me-PyCA)₃ clusters, Me-PyA, and Cu₂O under solvothermal conditions. As a comparison, methyl-free NonMe-Cu₃-MOF and UniMe-Cu₃-MOF, in which only one half of the copper sites were near the methyl group, were also successfully synthesized using a similar method. The crystalline structure of the MOF was confirmed using Materials Studio software based on the powder X-ray diffraction (PXRD) patterns. Fig. 1c shows that DiMe-Cu₃-MOF exhibited strong diffraction peaks at 4.7° and weaker reflections at approximately 8.1° and 26.1°, corresponding to the (100), (110), and (001) facets, respectively. Furthermore, the PXRD spectrum showed no presence of peaks corresponding to Cu₂O, indicating the complete removal of Cu₂O from the starting materials. DiMe-Cu₃-MOF was crystallized with an AA-eclipsed stacking model in the P3 space group. The simulated PXRD pattern, with an unweighted-profile *R* factor (*R*_p) of 4.60% and a weighted-profile *R* factor (*R*_{wp}) of 6.13%, matched very well with the experimentally observed curve, indicating the effectiveness of the proposed model (Scheme 1). The Pawley refinement method was employed to conduct a full spectrum fitting of the experimental diffraction pattern, resulting in the determination of the unit cell parameters for DiMe-Cu₃-MOF as follows: *a* = *b* = 22.0982 Å, *c* = 3.4883 Å, α = β = 90°, and γ = 120° (Scheme 1). These refinements indicate that DiMe-Cu₃-MOF possesses a 1D hexagonal channel along the *c*-axis, with a theoretical pore size

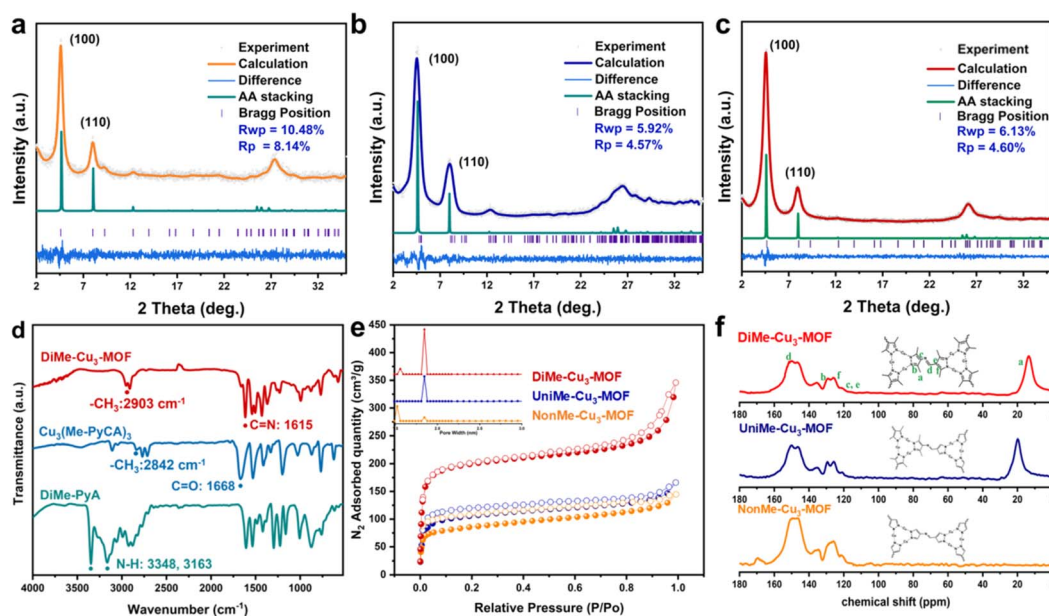


Fig. 1 Experimental diffraction patterns, patterns simulated from Pawley refinements (black), and patterns simulated from the structural model (green) for (a) NonMe-Cu₃-MOF, (b) UniMe-Cu₃-MOF and (c) DiMe-Cu₃-MOF. (d) The FT-IR spectra of DiMe-PyA, Cu₃(Me-PyCA)₃ and DiMe-Cu₃-MOF. (e) N₂ adsorption for NonMe-Cu₃-MOF, UniMe-Cu₃-MOF and DiMe-Cu₃-MOF. (f) ¹³C CP-MAS NMR spectra of UniMe-Cu₃-MOF, NonMe-Cu₃-MOF and DiMe-Cu₃-MOF.

of approximately 1.91 nm and a π - π stacking distance of 3.49 Å between adjacent layers along the *c*-axis. The NonMe-Cu₃-MOF and UniMe-Cu₃-MOF exhibit similar PXRD patterns to DiMe-Cu₃-MOF (Scheme 1 and Fig. 1a and b), suggesting that they are isomorphous materials.

The successful synthesis of DiMe-Cu₃-MOF, UniMe-Cu₃-MOF, and NonMe-Cu₃-MOF was further confirmed through Fourier transform infrared spectroscopy (FT-IR) and ¹³C solid-state cross-polarization magic angle-spinning nuclear magnetic resonance (CP-MAS NMR) spectroscopy. As shown in Fig. 1d and S1,† all three MOFs exhibited a newly formed C=N imine signal at approximately 1610 cm⁻¹, while the -CHO peak (1668 cm⁻¹) and -NH₂ signals (3201 cm⁻¹ and 3325 cm⁻¹) in the reactant monomers disappeared.⁴⁰ Furthermore, due to the increased conjugation (including planar conjugation and π - π stacking) of DiMe-Cu₃-MOF, a strong inductive effect is generated on the -CH₃ groups, leading to an increase in their bond strength. Consequently, the peak located at 2903 cm⁻¹ for the -CH₃ group in DiMe-Cu₃-MOF shows a blue shift in comparison with the peak at 2842 cm⁻¹ in Cu₃(Me-PyCA)₃. These results were supported by the ¹³C solid-state NMR spectrum (Fig. 1f), which showed a strong C=N imine carbon resonance signal at ~149 ppm and a prominent -CH₃ signal at 19 ppm in DiMe-Cu₃-MOF. Notably, the absence of methyl peaks was observed in NonMe-Cu₃-MOF. Inductively coupled plasma (ICP) spectroscopy confirmed that DiMe-Cu₃-MOF, UniMe-Cu₃-MOF, and NonMe-Cu₃-MOF had large Cu contents of 28.7 wt%, 32.7 wt%, and 41.1 wt%, respectively, indicating the integration of a large number of Cu catalytic sites into the MOF framework. N₂ adsorption experiments were conducted to investigate the porosity of DiMe-Cu₃-MOF, UniMe-Cu₃-MOF, and NonMe-Cu₃-MOF. The N₂ isotherms of DiMe-Cu₃-MOF at 77 K displayed type IV adsorption curves with hysteresis loops, indicating the

presence of micropores. Further analysis of the pore size distribution revealed that DiMe-Cu₃-MOF had micropores with an average diameter of approximately 1.85 nm (Fig. 1e and S2†), which closely corresponded to the theoretical value of 1.91 nm. The obtained DiMe-Cu₃-MOF exhibited the highest Brunauer–Emmett–Teller (BET) surface area of 772 m² g⁻¹ among the three MOFs. The UniMe-Cu₃-MOF had a BET surface area of 410 m² g⁻¹, sharing the same pore diameter of 1.85 nm, while the NonMe-Cu₃-MOF still had a moderate BET surface area of 318 m² g⁻¹, along with a slightly smaller pore diameter of 1.83 nm. Such high porosity of the three materials is favorable for the accessibility and transformation of NO₃⁻.

The scanning electron microscopy (SEM) images showed that all three MOFs have a dendritic crystal morphology (Fig. S3†). High-resolution TEM (HR-TEM) images (Fig. 2a–c) show that the ordered micropore lattice spacing of NonMe-Cu₃-MOF, UniMe-Cu₃-MOF, and DiMe-Cu₃-MOF is approximately 1.88 nm, 1.87 nm, and 1.85 nm, respectively, which is consistent with the pore size of the simulated structural model and N₂ adsorption results (Fig. 1e). Furthermore, the absence of a Cu₂O lattice within the three MOFs provides additional confirmation of the successful removal of Cu₂O from the initial materials. Energy-dispersive X-ray spectroscopy (EDS) element mapping images show that Cu, C and N elements are uniformly distributed across the structures of NonMe-Cu₃-MOF, UniMe-Cu₃-MOF, and DiMe-Cu₃-MOF (Fig. 2d–f).

X-ray absorption spectroscopy (XAS) was conducted to determine the oxidation state and coordination environment of copper species in the catalysts. In the Cu K-edge of X-ray absorption near edge structure (XANES) spectra for DiMe-Cu₃-MOF, the absorption edge corresponding to the 1s → 4p transition is positioned between Cu foil and Cu₂O, closer to Cu₂O. At the same time, the absence of the 1s → 3d pre-edge due to

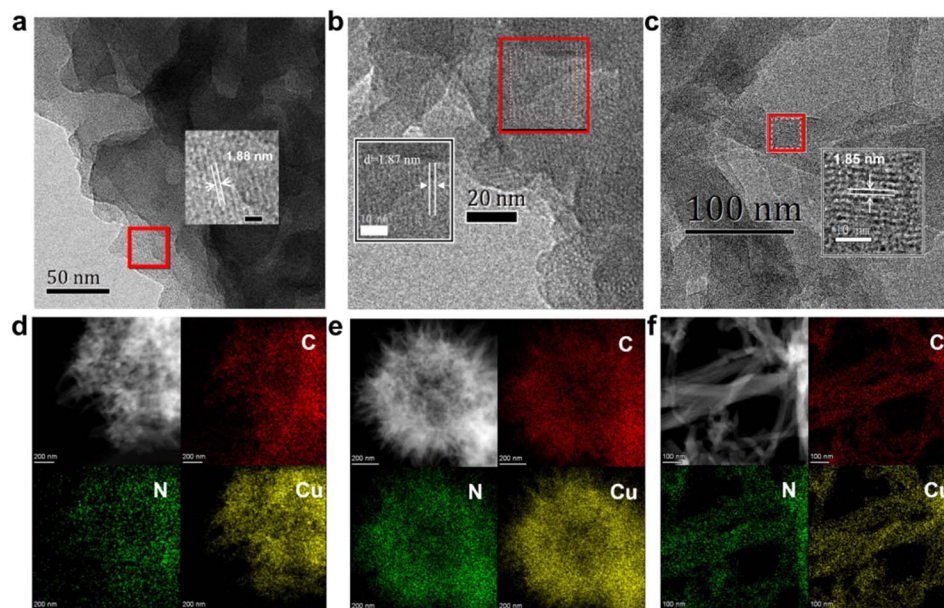


Fig. 2 HR-TEM image and the lattice distance of (a) NonMe-Cu₃-MOF, (b) UniMe-Cu₃-MOF and (c) DiMe-Cu₃-MOF. (d–f) HAADF-STEM image of (d) NonMe-Cu₃-MOF, (e) UniMe-Cu₃-MOF and (f) DiMe-Cu₃-MOF and the corresponding C, N, and Cu EDS elemental mappings.



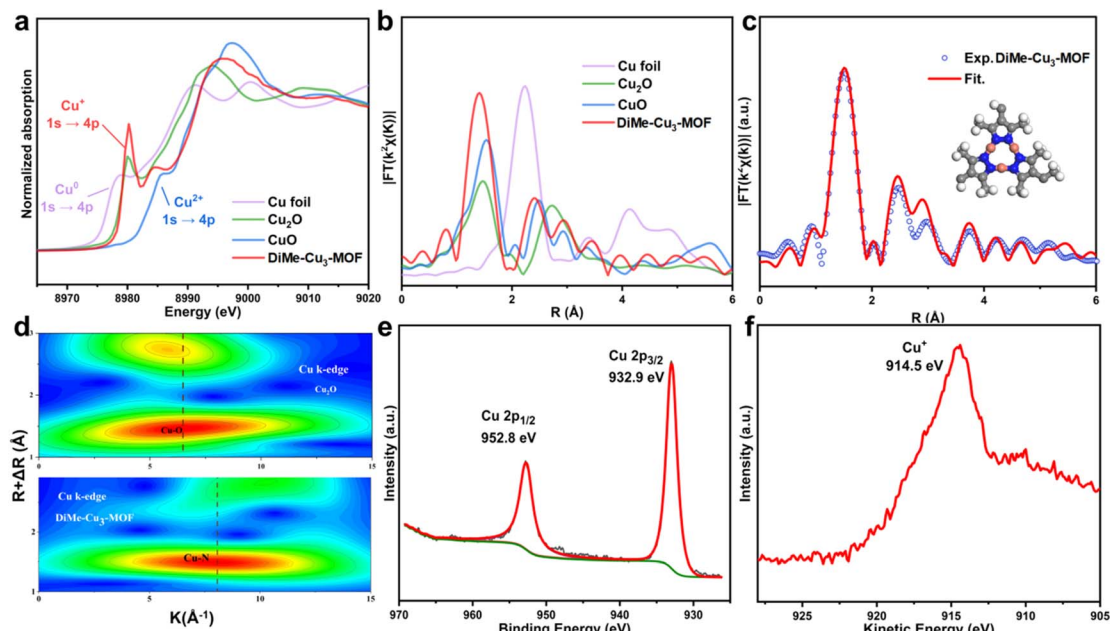


Fig. 3 (a) Cu K-edge of XANES spectra of DiMe-Cu₃-MOF, Cu foil, CuO and Cu₂O. (b) Cu K-edge of EXAFS spectra of DiMe-Cu₃-MOF, Cu foil, CuO and Cu₂O. (c) The EXAFS fitting curves of DiMe-Cu₃-MOF. (d) WT-EXAFS plots of DiMe-Cu₃-MOF and Cu₂O. (e) Cu 2p XPS spectra and (f) Cu LMM Auger spectra of DiMe-Cu₃-MOF.

the dipole-forbidden indicated the absence of Cu²⁺ in DiMe-Cu₃-MOF (Fig. 3a). It suggests that the oxidation state of copper in the material is +1. Additionally, in the Cu K-edge extended X-ray absorption fine structure (EXAFS) of DiMe-Cu₃-MOF (Fig. 3b), a clear signal corresponding to the Cu–N coordination path at 1.4 Å was observed, which differs from that of Cu₂O. Furthermore, no signal corresponding to Cu–Cu at 2.23 Å was observed, indicating there is no Cu or CuO_x in DiMe-Cu₃-MOF. Through comprehensive resolution in both K and R space, the wavelet transform (WT) analysis of Cu K-edge EXAFS was performed to further explore the coordination structure of DiMe-Cu₃-MOF. Fig. 3d illustrates the distinctive features of DiMe-Cu₃-MOF compared to Cu₂O, providing further evidence of the absence of Cu₂O particles and a non-Cu–O coordination mode in DiMe-Cu₃-MOF. The results indicated the dominance of Cu–N species and the absence of Cu and Cu₂O particles in DiMe-Cu₃-MOF. The EXAFS fitting spectrum (Fig. 3c and Table S1†) demonstrated a coordination number of 2.0 for the copper center in DiMe-Cu₃-MOF, which is consistent with the simulated structure. In addition, the Cu K-edge XANES and EXAFS spectra of UniMe-Cu₃-MOF and NonMe-Cu₃-MOF are also characterized in Fig. S4 and S5 and Tables S2 and S3.† According to the analysis results based on the Cu K-edge XANES and EXAFS curves in Fig. 3a and b, the Cu species in UniMe-Cu₃-MOF and NonMe-Cu₃-MOF exhibited similar states and coordination environments to the Cu in DiMe-Cu₃-MOF, which was coordinated by two N atoms (Fig. S4 and S5 and Tables S2 and S3†). High-resolution X-ray photoelectron spectroscopy (XPS) of Cu 2p reveals two peaks at 952.8 eV and 932.9 eV in DiMe-Cu₃-MOF, corresponding to Cu 2p_{1/2} and Cu 2p_{3/2}, respectively (Fig. 3e). Cu LMM Auger spectroscopy provided further

elucidation of the valence state of the copper center, revealing a Cu⁺ peak with a kinetic energy of 914.5 eV in DiMe-Cu₃-MOF (Fig. 3f). The XPS data for UniMe-Cu₃-MOF and NonMe-Cu₃-MOF showed similar results (Fig. S4 (e and f) and S5 (d and e)†) to those of DiMe-Cu₃-MOF, confirming the previous conclusion from X-ray absorption near-edge structure (XANES) that copper in the three MOFs exhibits a Cu⁺ state.

In order to evaluate the influence of hydrogen bonding on the intermediates of the NO₃RR, the activity of DiMe-Cu₃-MOF, UniMe-Cu₃-MOF, and NonMe-Cu₃-MOF in the NO₃RR was studied in a standard three-electrode H-cell. All the potentials mentioned in this work were referenced to Ag/AgCl. The ammonia generated after electrolysis was analyzed using ultraviolet-visible (UV-vis) spectrophotometry (Fig. S6†), and the accuracy of this method was verified by ion chromatography (IC) (Fig. S7†). There were significant differences in the electrochemical NO₃RR between DiMe-Cu₃-MOF and its corresponding control samples. As illustrated in Fig. 4a and S8,† the DiMe-Cu₃-MOF, which features –CH₃ groups in both Cu-CTUs, demonstrated a more positive onset potential, larger ammonia faradaic efficiencies (FE_{NH3}), and higher partial current densities when compared to the NonMe-Cu₃-MOF (lacking –CH₃ groups) and UniMe-Cu₃-MOF (with only half of Cu-CTUs containing –CH₃ groups). Especially, the current density for NonMe-Cu₃-MOF was much lower than those of the other two catalysts, indicating its poor activity for the NO₃RR. The ammonia yield and FE_{NH3} of the NO₃RR for the three catalysts are shown in Fig. 4b and c, respectively. DiMe-Cu₃-MOF achieved an FE_{NH3} of 95% at –1.55 V, with an ammonia yield of 401 μg h^{–1} cm^{–2} and a current density of –64 mA cm^{–2} (Fig. 4d). The ammonia yield of the NO₃RR for the three

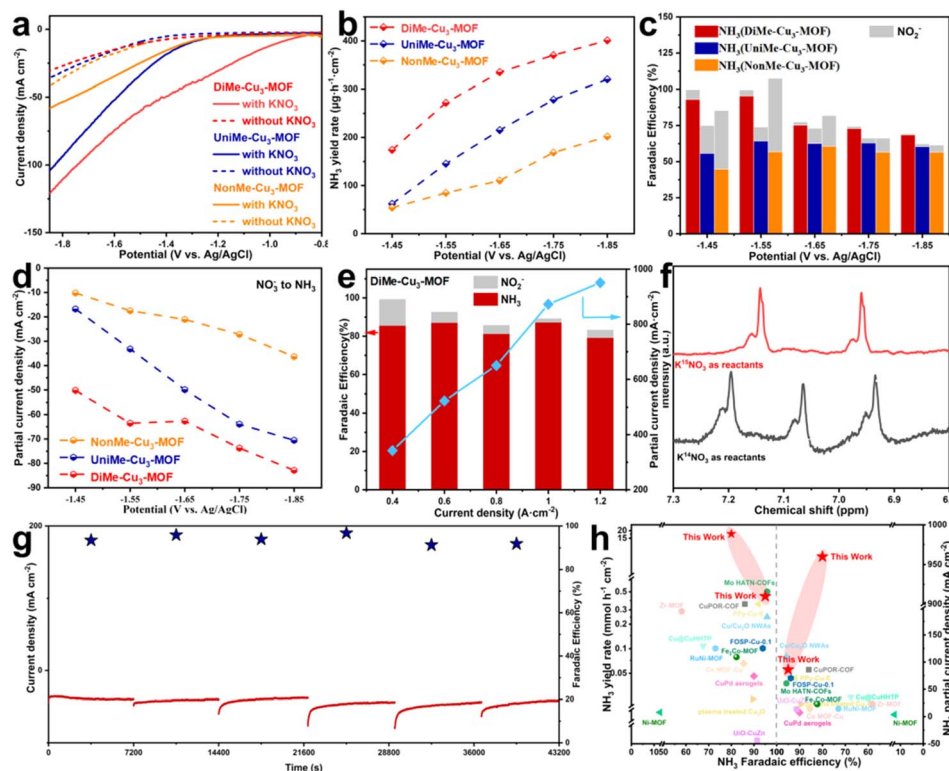


Fig. 4 (a) LSV polarization curves of DiMe-Cu₃-MOF, UniMe-Cu₃-MOF, and NonMe-Cu₃-MOF with and without 0.5 M K₂SO₄ and 50 mM KNO₃ electrolytes, respectively. (b) Comparison of NH₃ yields of DiMe-Cu₃-MOF, UniMe-Cu₃-MOF, and NonMe-Cu₃-MOF. (c) The comparison of NH₃ and NO₃[−] faradaic efficiencies of DiMe-Cu₃-MOF, UniMe-Cu₃-MOF, and NonMe-Cu₃-MOF. (d) The partial current densities of NH₃ evolution for different catalysts with 50 mM KNO₃. (e) NH₃ and NO₂[−] Faradaic efficiency and the partial current densities of NH₃ of DiMe-Cu₃-MOF under current-controlled conditions. (f) ¹H NMR spectra of the products after 2 h electrolysis with the electrolytes containing 50 mM ¹⁴KNO₃ or ¹⁵KNO₃ as the feeding nitrate source using DiMe-Cu₃-MOF. (g) Current densities of DiMe-Cu₃-MOF during continuous electrolysis in 0.5 M K₂SO₄ and 50 mM KNO₃ electrolytes at −1.45 V for 12 h (bottom panel) and the corresponding FE_{NH₃} (top panel). (h) Comparison of the NO₃RR performance of the DiMe-Cu₃-MOF with other catalysts reported in the literature.

materials increased in the order of NonMe-Cu₃-MOF < UniMe-Cu₃-MOF < DiMe-Cu₃-MOF. The FE_{NH₃} of NonMe-Cu₃-MOF was significantly lower than that of UniMe-Cu₃-MOF and DiMe-Cu₃-MOF within the potential range of −1.45 to −1.85 V. In contrast, the production of NO₃[−] was determined by a typical colorimetric method to evaluate the corresponding electrocatalytic performance (Fig. S9†).⁴¹ The results show that NO₂[−] content generated by NonMe-Cu₃-MOF is higher than those of the other two catalysts, indicating that the NO₂[−] intermediate escaped from the Cu active sites, which was not further transformed to NH₃. It may be ascribed to the NO₂[−] intermediate that cannot be stabilized by the Cu sites of NonMe-Cu₃-MOF. This highlights the importance of introducing methyl groups into DiMe-Cu₃-MOF to stabilize intermediates *via* hydrogen bonding. To further verify the industrial applicability of DiMe-Cu₃-MOF, NO₃RR tests were conducted under constant current electrolysis conditions. The results demonstrated that within the current density range of −400 to −1200 mA cm^{−2}, DiMe-Cu₃-MOF consistently maintains an FE_{NH₃} above 80%, with the partial current density for ammonia reaching −950.6 mA cm^{−2} (Fig. 4e). In addition, DiMe-Cu₃-MOF has high stability, in which the current density remained consistent throughout a 12

hour testing period, as well as without any notable decline in Faraday efficiency (Fig. 4g). PXRD patterns, TEM images and Cu K-edge EXAFS and EXAFS showed no significant changes in DiMe-Cu₃-MOF after 2 h of electrolysis compared to the corresponding freshly prepared material (Fig. S10–S12†).

To confirm the source of the NH₃ product for DiMe-Cu₃-MOF, a series of control experiments and ¹⁵N isotope-labeled experiments were conducted.^{42,43} When nitrate was not added to the electrolyte or applied open circuit potential, no ammonia was produced (Fig. S13†). Additionally, by using ¹⁵NO₃[−] as the nitrogen source, the origin of ammonia was traced to the nitrate in the electrolyte rather than environmental contamination. The typical double-peak ¹⁵NH₃ signal effectively ruled out ammonia contamination and confirmed that ammonia was indeed produced through the electrocatalytic reduction of NO₃[−] (Fig. 4f).

In order to determine whether the high activity of DiMe-Cu₃-MOF originates from the effect of atypical hydrogen bonding in the NO₃RR process, the activities are normalized by the number of redox-active copper sites, BET surface areas and the loading amount of catalysts on the electrode. As shown in Fig. S14 and S15 and Table S4,† DiMe-Cu₃-MOF showed moderate intrinsic



activity for the NO_3RR towards NH_3 from the ECSA-normalized I - V curves, indicating that the high performance of DiMe-Cu₃-MOF is not from its high ECSA. Additionally, when the activity was normalized by the BET surface area, the DiMe-Cu₃-MOF also showed moderate intrinsic activity for the NO_3RR towards NH_3 at moderate current density, which suggested that the high activity of DiMe-Cu₃-MOF is not contributed by its high surface area (Fig. S16[†]). Meanwhile, different loading amounts on the electrode showed similar normalized current density and ammonia Faraday efficiency, indicating that the amount of the catalyst loading on the electrode had little effect on the catalytic activity (Fig. S17[†]). These results demonstrated that the high activity of DiMe-Cu₃-MOF toward NH_3 can be attributed to the effect of atypical hydrogen bonding. In order to elucidate the role of hydrogen bonds in the stabilization of intermediates in the NO_3RR process, *in situ* Fourier transform infrared spectroscopy (*in situ* FTIR) measurements were carried out (Fig. S18[†]). As shown in Fig. 5a, b and S19,[†] the downward absorption band at 1380 cm^{-1} corresponds to the consumption peak of NO_3^- . With increasing potential, two distinct peaks

corresponding to the vertical and bending adsorption of NO appear at $\sim 1730\text{ cm}^{-1}$ and 1649 cm^{-1} , respectively, in DiMe-Cu₃-MOF (Fig. 5a). As the applied potential increases, the intensity of these peaks decreases more noticeably. Additionally, as shown in Fig. 5b, with the increase of potential, the vertical and bending adsorption peaks of NO appear at $\sim 1778\text{ cm}^{-1}$ and 1643 cm^{-1} and their intensities increase significantly in NonMe-Cu₃-MOF. However, after reaching the optimal point, the absorption peak decreases slightly. This indicates that NonMe-Cu₃-MOF has a weaker ability to facilitate the conversion of NO_2 into NO intermediates, which is different from DiMe-Cu₃-MOF as shown in Fig. 5a, further illustrating the role of DiMe-Cu₃-MOF in stabilizing NO_2 intermediates. The trend of increasing absorption peaks with potential increase for NO_2 (1550 cm^{-1}) intermediates on NonMe-Cu₃-MOF indicates the gradual accumulation of NO_2 (Fig. 5b).^{44,45}

In situ Raman spectra were utilized further to investigate the catalyst surface during the reaction. The Raman peaks at 986 and $\sim 1046\text{ cm}^{-1}$ correspond to the characteristic vibration modes of SO_4^{2-} and NO_3^- in the electrolyte, respectively. The

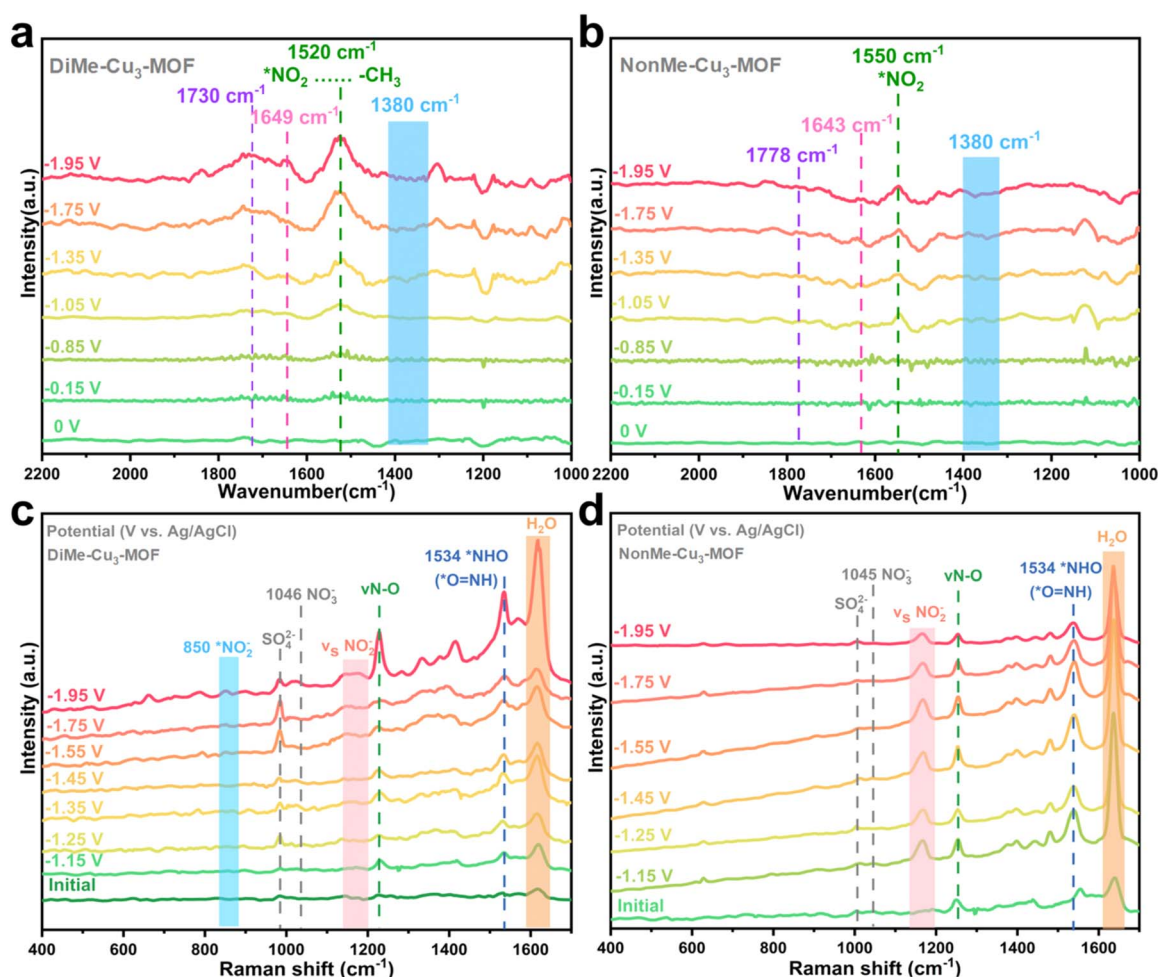


Fig. 5 (a) *Operando* ATR-FTIR spectra collected at different applied voltages for DiMe-Cu₃-MOF in 50 mM KNO_3 and 0.5 M K_2SO_4 electrolytes and (b) *Operando* ATR-FTIR spectra collected at different applied voltages for NonMe-Cu₃-MOF in 50 mM KNO_3 and 0.5 M K_2SO_4 electrolytes. (c) *Operando* Raman spectra of DiMe-Cu₃-MOF collected at different applied potentials in 50 mM KNO_3 and 0.5 M K_2SO_4 electrolytes and (d) *Operando* Raman spectra of NonMe-Cu₃-MOF collected at different applied potentials in 50 mM KNO_3 and 0.5 M K_2SO_4 electrolytes.



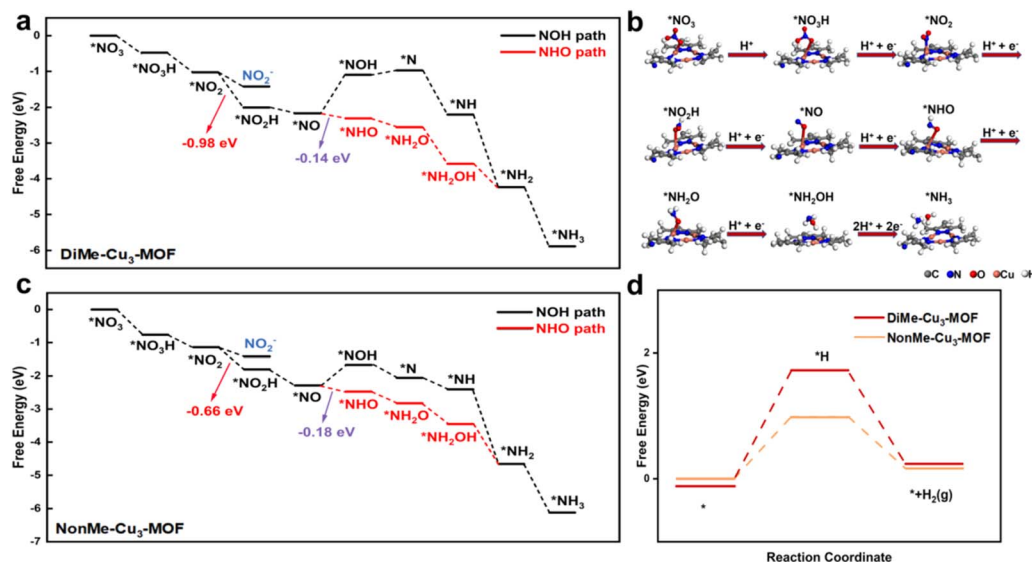


Fig. 6 (a) Gibbs free energy diagram for the NO₃RR on DiMe-Cu₃-MOF. (b) The most probable pathway of the NO₃RR on DiMe-Cu₃-MOF (side view). (c) Gibbs free energy diagram for the NO₃RR on NonMe-Cu₃-MOF. (d) Gibbs free energy diagram for the HER on DiMe-Cu₃-MOF and NonMe-Cu₃-MOF.

DiMe-Cu₃-MOF shows a Raman peak of the Cu–N bond at 454 cm⁻¹ (Fig. 5c and S20†). The intensity of this peak initially increases and then decreases with the rising potential, suggesting an accumulation of the Cu–N bond at low potential, followed by the consumption of the intermediate of the NO₃RR at high potential. The Raman peaks at 850, 1160, 1221 and 1534 cm⁻¹ are related to the symmetric and antisymmetric stretching vibrations of chelated NO₂⁻, *NO and *NHO intermediates, respectively.^{46,47} Therefore, the combination of catalytic performance, *in situ* FTIR and Raman spectroscopy results demonstrates that DiMe-Cu₃-MOF exhibits stronger intermediate (*NO₂) adsorption compared to other materials, leading to excellent NO₃RR performance.

To study the effects of hydrogen bonding on the NO₃RR and HER, DFT calculations were performed for the DiMe-Cu₃-MOF and NonMe-Cu₃-MOF. Two typical NO₃RR pathways were considered: the NOH pathway (*NO₃⁻ → *NO₂ → *NO₂H → *NO → *NOH → *N → *NH → *NH₂ → *NH₃) and the NHO pathway (*NO₃⁻ → *NO₂ → *NO₂H → *NO → *NHO → *NH₂O → *NH₂OH → *NH₂ → *NH₃), respectively. According to *in situ* Raman results, the presence of the *NHO intermediate instead of the *NOH (1540 cm⁻¹) intermediate was detected on both DiMe-Cu₃-MOF and NonMe-Cu₃-MOF, indicating that the nitrate was reduced to ammonia *via* the NHO pathway (Fig. 5c, d and S21†).⁴⁸ As illustrated in Fig. 6a and c, the conversion from *NO to *NHO is identified as the rate-determining step (RDS). However, the difference in the Gibbs free energy (Δ*G*) for DiMe-Cu₃-MOF (-0.14 eV) and NonMe-Cu₃-MOF (-0.18 eV) for the conversion from *NO to *NHO is minimal. In the case where the difference in Δ*G* for the RDS is not significant, DiMe-Cu₃-MOF and NonMe-Cu₃-MOF exhibit pronounced performance distinctions, primarily attributed to the hydrogen bonding interaction between DiMe-Cu₃-MOF and *NO₂ during the NO₃RR process. DFT calculations were employed to further

elucidate how the hydrogen bonding interaction facilitates the performance of the NO₃RR to ammonia. As shown in Fig. 6a, the Δ*G* of the conversion from the *NO₂ intermediate to *NO₂H over DiMe-Cu₃-MOF (-0.98 eV) is lower than that of NonMe-Cu₃-MOF (-0.66 eV, Fig. 6c), indicating thermodynamically favorable ammonia generation. This is primarily attributed to the hydrogen bonding interaction stabilizing the *NO₂ intermediate in the reaction process of DiMe-Cu₃-MOF, which has been experimentally confirmed by *in situ* FTIR spectroscopy. In addition, the free energy of the HER of DiMe-Cu₃-MOF is higher than that of NonMe-Cu₃-MOF, indicating that the introduction of the methyl group could impede the HER (Fig. 6d), which is consistent with the results of electrochemical experiments. Additionally, the noncovalent interaction (NCI) was further applied to illustrate the hydrogen bond.⁴⁹ As shown in Fig. S22,† an obvious van der Waals interaction was observed between the methyl groups and intermediates, indicating that the existence of a hydrogen bond could stabilize the intermediates of the NO₃RR. Based on the analysis of the NO₃RR and HER, we propose that the formation of hydrogen bonding by adjusting the microenvironment of the active center can promote the NO₃RR by stabilizing the *NO₂ intermediate and reducing the energy barrier in the rate-limiting *NO₂H generation step, thus promoting the NO₃RR.

Conclusions

In conclusion, drawing inspiration from the natural nitrogenase, we have developed an effective strategy to promote the NO₃RR on MOFs by introducing appropriate groups into copper-based electrocatalytic materials to stabilize the intermediate *NO₂ through hydrogen bonding. By manipulating the microenvironment of Cu-CTU-based MOFs in the reduction process, we have constructed catalytic materials with trinuclear



copper centers for nitrate. Therefore, the NO₃RR activity of DiMe-Cu₃-MOF, which can form hydrogen bonds with intermediates, is significantly higher than that of UniMe-Cu₃-MOF, which can partially form hydrogen bonds, and NonMe-Cu₃-MOF, which cannot form hydrogen bonds. The DiMe-Cu₃-MOF electrocatalyst provides a high NH₃ Faradaic efficiency of 95% at −1.55 V and reaches a current density of −950.6 mA cm^{−2}. The NH₃ production rate reaches a high activity of 401 μg cm^{−2} h^{−1} and maintains an FE_{NH₃} of about 80% at high current density (−1.2 A cm^{−2}), surpassing all reported MOF/COF materials and most other copper-based catalysts. *In situ* infrared spectroscopy confirms the existence of hydrogen bonds between MOF materials and the key intermediate *NO₂, and DFT calculations elucidate that the presence of hydrogen bonds reduces the energy barrier in the rate-limiting *NO₂H generation step, thereby promoting NH₃ production. This study provides new insights into the importance of stabilizing the key intermediate *NO₂ and reducing the local binding energy of H₂O to enhance the NO₃RR.

Data availability

https://app.globus.org/file-manager?origin_id=82f1b5c6-6e9b-11e5-ba47-22000b92c6ec&origin_path=%2Ftmp%2FRaw+data%2F.

Author contributions

Rong Cao and Yuan-Biao Huang proposed the research direction, were responsible for the infrastructure, guided the project, and revised the paper. Xiao-Xue Fu, Hui Guo and Hong-Jing Zhu realized the experiments, performed the characterization, and wrote the paper. Duan-Hui Si conducts the computational study. Yi-Ying Lan assisted with the experiments and characterization. All authors commented on the manuscript.

Conflicts of interest

The authors declare no competing financial interest.

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