

## Minireview



## Sustainable Chemistry

How to cite: Angew. Chem. Int. Ed. 2025, e202509053 doi.org/10.1002/anie.202509053

# **Electrochemical Synthesis of Hydroxylamine**

Minghao Guo, Yuhan Zhang, Chengying Guo,\* and Yifu Yu\*

**Abstract:** Hydroxylamine (NH<sub>2</sub>OH) serves as an important industrial feedstock. The conventional production and transportation of NH<sub>2</sub>OH requires harsh conditions. Recently, electrochemical hydrogenation of nitrogencontaining oxidative species, such as nitrate, nitrite, and nitric oxide (NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>/NO), into NH<sub>2</sub>OH has been developed as a sustainable strategy. However, the over-hydrogenation product of ammonia is preferentially obtained under electroreduction condition. Thus, the rational design of catalysts structure is crucial to selective electrosynthesis of NH2OH. In this minireview, we summarize recent advances in electrochemical synthesis of NH<sub>2</sub>OH with emphasis on the design of catalysts structure. Electrochemical synthesis strategy we discussed is categorized by the existence form of product, including indirect electrosynthesis and direct electrosynthesis. Finally, the techno-economic analysis (TEA) of electrochemical NH2OH production and outlook of performance improvement strategies are carried out to further guide the optimization of reaction system.

#### 1. Introduction

Hydroxylamine (NH<sub>2</sub>OH), as an important industrial feedstock, has been widely used in nylon, medicine, fuel, and agrochemical<sup>[1,2]</sup> The conventional craft for NH<sub>2</sub>OH production rely on complex thermocatalytic reactions, which require harsh conditions (Scheme 1a).<sup>[3–7]</sup> Meanwhile, the toxic and explosive risks of NH<sub>2</sub>OH cause difficulties during transportation and storage. Thus, it is of great significance to develop a sustainable technique to in-place produce NH<sub>2</sub>OH for downstream application. Interestingly, numerous works have reported the electroreduction of nitrogen-containing

[\*] M. Guo, Prof. Y. Yu

National Industry-Education Platform for Energy Storage, Tianjin University, Tianjin 300350, China

E-mail: yyu@tju.edu.cn

M. Guo, Y. Zhang, Dr. C. Guo, Prof. Y. Yu Institute of Molecular Plus, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China E-mail: guocy\_@tju.edu.cn

Dr. C. Guo

Haihe Laboratory of Sustainable Chemical Transformations, Tianjin 300192, China

Additional supporting information can be found online in the Supporting Information section oxidative species including nitrate, nitrite, and nitric oxide  $(NO_3^-/NO_2^-/NO)$  to ammonia  $(NH_3)$ , in which  $NH_2OH$  was usually found as an intermediate. [8–13] Compared with  $NH_3$ ,  $NH_2OH$  has much higher value  $(1600 \$ \cdot ton_{NH2OH}^{-1} \text{ versus } 600 \$ \cdot ton_{NH3}^{-1})$ . Thus, electroreduction of  $NO_3^-/NO_2^-/NO$  provides a sustainable strategy for in-place production of  $NH_2OH$ . However, the theoretical reduction potential of  $NH_2OH$  to  $NH_3$  is +1.35 V (versus NHE). [14] The very positive potential indicates that  $NH_2OH$  is unstable and easily over-reduced to  $NH_3$  during electroreduction process. Therefore, the rational design of catalytic system is crucial to selective electrosynthesis of  $NH_2OH$ .

To date, electrochemical synthesis of NH<sub>2</sub>OH from NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>/NO follows two categories (Scheme 1b): 1) Indirect electrosynthesis: in situ capture of NH<sub>2</sub>OH intermediate (\*NH<sub>2</sub>OH) by spontaneous oximation reaction with aldehyde/ketone and then NH<sub>2</sub>OH is obtained after oximation hydrolyze. 2) Direct electrosynthesis: selective hydrogenation of NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>/NO to directly generate NH<sub>2</sub>OH. In this minireview, we summarize recent advances in the electrochemical synthesis of NH<sub>2</sub>OH with emphasis on the aforementioned two strategies. To further guide the application of reaction system in the future, we carry out techno–economic analysis (TEA) with faradaic efficiency (FE) and current density (*j*) of NH<sub>2</sub>OH as the two key parameters. Finally, we outlook catalyst design and reactor engineering to improve the reactive activity and energy efficiency purposefully.

#### 2. Indirect Electrosynthesis of NH2OH

Industrially, NH<sub>2</sub>OH is produced by oxime hydrolysis and oxime is usually synthesized by spontaneous nucleophilic addition-elimination reaction between unstable NH<sub>2</sub>OH intermediate and trapping agent of aldehyde/ketone (RCOH/RCOR). Thus, oxime can also be formed by in situ capturing \*NH2OH intermediate with RCOH/RCOR during electroreduction. As a result, NH<sub>2</sub>OH is indirectly electrochemical synthesis. Recently, dozens of oximes have been obtained by in situ capturing \*NH2OH through adsorbed or free RCOH/RCOR (1. \*NH<sub>2</sub>OH + RCOH/RCOR  $\rightarrow$  oxime, 2. \*NH<sub>2</sub>OH + \*RCOH/\*RCOR → oxime, Figure 1).<sup>[15–18]</sup> Zhang's group proposed the mechanism of oxime generation during NO<sub>3</sub><sup>-</sup>RR, in which the over-reduction of \*NH<sub>2</sub>OH to NH<sub>3</sub> competes with the oximation reaction.<sup>[19]</sup> So, the stabilization and enrichment of \*NH2OH is a possible direction for catalyst design. It was reported that the desorption of \*NH2OH was promoted thermodynamically via alloying Zn and Cu, and thus NH<sub>2</sub>OH could be stabilized.<sup>[20]</sup> Moreover, \*NH<sub>2</sub>OH could be enriched over Fe nanoparticles via increasing the activation barrier for further hydrogenation of \*NH2OH  $(*NH<sub>2</sub>OH \rightarrow *NH<sub>2</sub>).$ <sup>[21]</sup> The indirect synthesis performances are summarized in Table S1, in which the C-selectivity has been achieved almost 100%, but the N-selectivity is still low. Higher N-selectivity could be achieved by increasing the concentration of capture agent, but the C-selectivity is bound to decrease. Thus, the development of novel strategies to simultaneously improve the C-selectivity and N-selectivity is highly requirable.

## 3. Direct Electrosynthesis of NH2OH

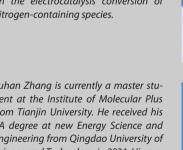
Comparing NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup> reduction and NO reduction, \*NO is formed by NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup> reduction and NO adsorption, respectively. Thus, the mechanistic difference between NO reduction and NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup> reduction lies in the formation process of \*NO. For NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup> reduction, NO is the possible by-product, thus high hydrogenation ability is needed to reduce \*NO, but it enhances the competition between NH<sub>3</sub> and NH<sub>2</sub>OH in turn. For NO electroreduction, the reactant NO exists in the form of gas molecules, so the hydrogenation of \*NO must take into account of NO enrichment and adsorption. For the hydrogenation of \*NO, it is shared in NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>/NO electroreduction and determines the selectivity for NH<sub>3</sub> or NH<sub>2</sub>OH.

NH<sub>2</sub>OH has been identified as an unstable intermediate during NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>/NO electroreduction, with a propensity to undergo over-hydrogenation to NH<sub>3</sub>. Single-atom catalysts (SACs) have been widely used in direct electrosynthesis of NH<sub>2</sub>OH owing to two advantages as follows (Figure 2a). 1) SACs modulated the adsorption configuration of reactants to selectively generate \*NH2OH. Zhou et al. simultaneously synthesized Co-based catalysts with single atom and nanoparticles (NPs) structure to explore the relationship between NH<sub>2</sub>OH selectivity and adsorption configuration, which is related to catalyst structure. [22] In situ attenuated total reflection fourier-transform infrared (ATR-FTIR) spectra proved the linear and bridge adsorption of \*NO on Co SACs and Co NPs, respectively. The linear adsorption of \*NO brings the maintenance of N-O bond during electroreduction, resulting in the selective generation of  $NH_2OH$  (FE<sub>NH2OH</sub> = 81.3%). On the contrary, the bridge adsorption of \*NO induces the breaking of N-O bond during electroreduction, resulting in the selective generation of ammonia ( $FE_{NH3} = 92.3\%$ ). Furthermore, Wu et al. confirmed the maintenance of N-O bond on SACs during reduction reaction by calculations.<sup>[23]</sup> 2) SACs possessed the weak absorption ability for \*NH2OH and exhibited spontaneous thermodynamic desorption properties to selectively generate NH<sub>2</sub>OH. Generally, the isolated active site of SACs anchored by N/C atoms brings partial positive charge, which weaken the adsorption strength of \*NH2OH and exhibits high selectivity for NH<sub>2</sub>OH.<sup>[24,25]</sup> It has been reported that the real active species is positive charged Fe2+ in Fe-SACs during NO electroreduction through in situ X-ray absorption near edge structure (XANES) spectra, which directly proved the positive charge of SACs for NH2OH selective synthesis  $(FE_{NH2OH} \approx 60\%).^{[26]}$ 

To achieve both high activity and selectivity, Yu's group proposed to utilize lattice hydrogen (H<sub>lat</sub>) with weaker reduc-



Minghao Guo is currently a doctoral candidate at the National Industry-Education Platform for Energy Storage and Institute of Molecular Plus in Tianjin University. He received his BA degree at the School of Chemical Engineering and Technology from Tianjin University in 2024. His current research focuses on the electrocatalysis conversion of nitrogen-containing species.





Chengying Guo received her PhD in materials physics and chemistry from Tianjin University in 2024. After completing her doctoral studies, she joined Institute of Molecular Plus in Tianjin University as an assistant researcher. Her research focuses on the design and development of advanced nanomaterials for electrocatalysis conversion of nitrogen- and carboncontaining species.

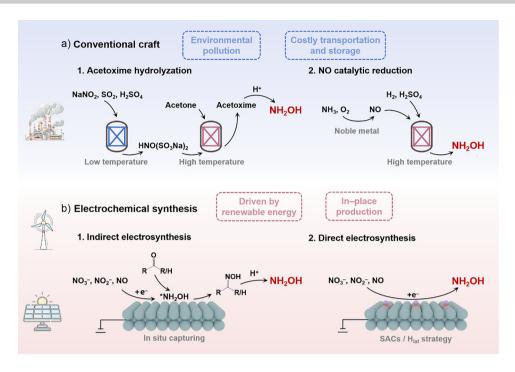
15213773, 0. Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/anie.202509053 by Tsinghua University Library, Wiley Online Library on 16/06/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/rems-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons Licenses



Yuhan Zhang is currently a master student at the Institute of Molecular Plus from Tianjin University. He received his BA degree at new Energy Science and Engineering from Qingdao University of Science and Technology in 2024. His current research focuses on the electrocatalysis conversion of nitrogen-containing species.



Yifu Yu received his BE and ME degrees in chemical engineering from Tianjin University. He obtained his PhD degree in chemical engineering from the same university in 2014. He worked as a postdoctoral fellow in Prof. Hua Zhang's group in the School of Materials Science and Engineering, Nanyang Technological University, Singapore, from 2014 to 2017. He is currently a Professor at Institute of Molecular Plus in Tianjin University. His research interests focus on heterogeneous catalysis of nitrogencontaining small molecules.



Scheme 1. a) Conventional craft of NH2OH production. b) Electrochemical synthesis of NH2OH via indirect and direct strategy.

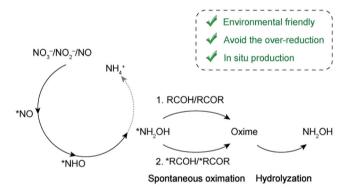


Figure 1. Schematic illustration for indirect NH2OH generation.

tion ability than active hydrogen (\*H) for NH2OH selective electrosynthesis (Figure 2b).[27] The proton is inserted into the lattice of MnO<sub>2</sub> catalysts to generate H<sub>lat</sub>, which directly participates in NO<sub>3</sub><sup>-</sup> hydrogenation and then produces H<sub>lat</sub> vacancy. Subsequently, the hydrogen tends to replenish the H<sub>lat</sub> vacancy rather than to form \*H. Thus, a dynamic balance between consumption and replenishment of H<sub>lat</sub> is achieved. The as-produced \*NH<sub>2</sub>OH tends to desorb from the surface of catalyst rather than be over-reduced to NH<sub>3</sub> when using  $H_{lat}$  as H-source owing to its weak reduction ability, confirming the buffer effect of H<sub>lat</sub>. Moreover, the doping of Cu can induce Cu-triggered Jahn-Teller distortion of [MnO<sub>6</sub>] octahedron, which significantly increases the number of H<sub>lat</sub>. As a result, the faradaic efficiency and yield of NH<sub>2</sub>OH achieve 91.1% and 396.6 mmol  $g_{cat.}^{-1} h^{-1}$ , respectively. Compared to \*H from water dissociation, H<sub>lat</sub> plays the dual-function of enrichment and buffer, which can provide abundant H<sub>lat</sub> for NO<sub>3</sub><sup>-</sup> selective reduction to



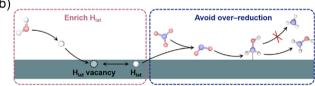


Figure 2. Schematic illustration for the direct electrosynthesis of  $NH_2OH$  a) over single-atom catalysts and nanoparticles, b) using  $H_{lat}$  as H-source.

NH<sub>2</sub>OH without over-hydrogenation. This work paved a new path for the design of efficient electrocatalysts for direct electrosynthesis of NH<sub>2</sub>OH.

#### 4. NH<sub>2</sub>OH Detection

In this section, we summarized two-type methods for detection and quantification of NH<sub>2</sub>OH based on the above-mentioned indirect electrosynthesis and direct electrosynthesis. For the indirect electrosynthesis, the \*NH<sub>2</sub>OH is captured

mbaded from https://onlinelibrary.wiely.com/doi/10.1002/anie.202509033 by Tsinghua University Library, Wiley Online Library on [16/06/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons Licenses

15213773, 0. Downloaded from https://onlinelibrary.wilej.com/doi/10.1002/ainie.202509053 by Tsinghua University Library, Wiley Online Library on [16/6/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/errms-and-conditions) on Wiley Online Library on rules of use; OA arctices are governed by the applicable Creative Commons License

by RCOH/RCOR to form oxime via a spontaneous oximation reaction. The formed oxime has <sup>1</sup>H nuclear magnetic resonance (<sup>1</sup>H NMR) characteristic peaks, which can be precisely detected and quantified by <sup>1</sup>H NMR method with suitable internal standard (such as dimethyl sulfoxide, maleic acid). In this method, the high stability of RCOH/RCOR and the high oximation rate during electrosynthesis process are important for the accuracy of the data. For the direct electrosynthesis, the free NH<sub>2</sub>OH is obtained in electrolyte. The <sup>1</sup>H NMR method can be also used to detect NH<sub>2</sub>OH after adding

RCOH/RCOR to as-produced electrolyte. In addition, the

colorimetric method is also widely used to directly quantify NH<sub>2</sub>OH in aqueous solution.<sup>[22,28]</sup> Notably, the <sup>1</sup>H NMR and

colorimetric methods can be carried out simultaneously to

### 5. Techno-Economic Analysis (TEA)

verify the accuracy of the data.

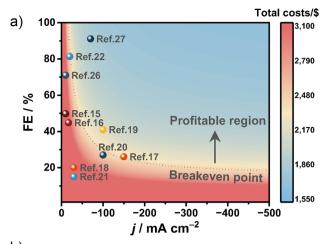
To assess the economic potential of in-place utilization of NH<sub>2</sub>OH driven by renewable electricity, a modified TEA model was employed with FE<sub>NH2OH</sub> and current density (j) as two key parameters (details in Supporting Information). The performances of recently reported works were added in this TEA picture, in which the improvement of  $FE_{NH2OH}$  or j is expected to achieve economic profitability (Figure 3a). In previous works (Table S1), the FE and j were around 50% and -50 mA cm<sup>-2</sup> in NH<sub>2</sub>OH generation, so the specific costs were directly quantified and provided as Figure 3b. It can be seen that the materials cost was dominant for NH<sub>2</sub>OH generation. When using N-containing wastewater as materials, the NH<sub>2</sub>OH generation has much higher economic profit and developing advanced catalysts to enrich low concentration nitrate in wastewater also exhibits high research prospect.

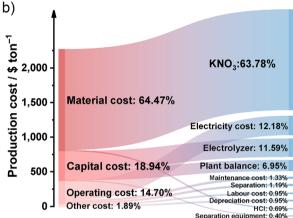
### 6. Summary and Outlook

Over past years, electroreduction of  $NO_3^-/NO_2^-/NO$  provides a sustainable strategy for in-place production of  $NH_2OH$ . Remarkable advancements have been made in indirect and direct electrosynthesis of  $NH_2OH$ . However, several challenges remain: 1) The low efficiency of indirect synthesis strategy and the incompatibility of activity and selectivity. 2) The limitation of traditional batch reactor on performance. In this section, we propose a few possible future directions for addressing the challenges of current researches.

#### 6.1. Catalyst Design

To improve the efficiency of indirect synthesis strategy, the spontaneous nucleophilic addition–elimination reaction efficiency between \*NH<sub>2</sub>OH and RCOH/RCOR needs to be further improved. As known, the nucleophilicity of \*NH<sub>2</sub>OH can be enhanced after the electron transfer from active site to





**Figure 3.** a) TEA result for in-place production of  $NH_2OH$  with FE and j as variates. b) Subdivided cost of the entire process for in-place production of  $NH_2OH$  by using nitrate as raw materials.

\*NH<sub>2</sub>OH. Thus, the construction of electron-rich active site is expected to improve the efficiency of nucleophilic attack.

To simultaneously improve the activity and selectivity of direct strategy, the adoption of  $H_{lat}$  is promising. As mentioned in section 3,  $Cu-MnO_2H_x$  can synthesize  $NH_2OH$  with high activity and selectivity via  $H_{lat}$ . But,  $MnO_2$  is not intrinsically active and has a large overpotential for  $H_{lat}$  generation. Thus, the design and construction of catalysts with thermodynamical advantage for the formation of  $H_{lat}$  is expected to reduce the overpotential for direct electrosynthesis of  $NH_2OH$ .

#### 6.2. Reactor Engineering

In addition to catalysts, the design of reactor to match reaction conditions is also a pathway to enhance performance of unstable products. NO<sub>3</sub><sup>-</sup>/NO<sub>2</sub><sup>-</sup>/NO electroreduction is usually done in batch H-type reactor. But, the ratio of electrode area to electrolyte volume and the mass transfer of batch reactor is lower than continuous flow cell, which inevitably increases the over-reduction of NH<sub>2</sub>OH to NH<sub>3</sub> (Figure 4a). Thus, we proposed two directions in reactor engineering.



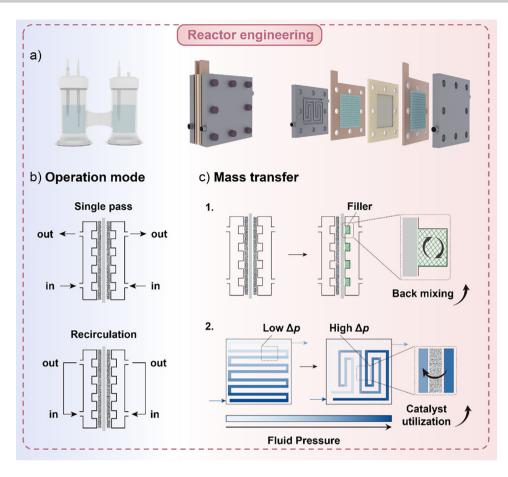


Figure 4. a) Scheme of batch H-type reactor and continuous flow cell. b) Scheme of different operation modes. c) Scheme of different mass transfer effect.

- (a) Operation mode: For indirect synthesis, high N-selectivity could be achieved using high concentration of capture agent, but C-selectivity of capturing agent is low. The recirculation operation can reuse the residual capture agent to improve utilization, achieving high C-selectivity and high N-selectivity simultaneously (Figure 4b down). For direct synthesis strategy, the obtained NH<sub>2</sub>OH is unstable and easily over-reduced to NH<sub>3</sub> during electroreduction process. The single-pass operation is an important operation mode to reduce the duration time of unstable NH<sub>2</sub>OH (Figure 4b up).
- (b) Mass transfer: Mass transfer plays a central role in continuous flow cell owing to the enhancement in reaction efficiency (Figure 4c). On one hand, filling the flow channels and loading catalyst on the filler can reduce concentration polarization and enhance radial mass transfer between electrode and electrolyte. For indirect electrosynthesis, the enhancement of mass transfer improves the capture efficiency. For direct electrosynthesis, it decreases the duration time of unstable NH<sub>2</sub>OH and thus improve the NH<sub>2</sub>OH activity and selectivity. On the other hand, there is a pressure difference ( $\Delta p$ ) between the flow channels due to the fluid drag. The high  $\Delta p$  can improve mass transfer in catalysts surface between the neighboring flow channels, resulting in the improvement of catalyst utilization. Therefore, rational

design of the flow channels sequence to increase  $\Delta p$  can improve the reactive activity and efficiency availably.

#### **Acknowledgements**

The authors thank the National Key Research and Development Program of China (2024YFA1510100) and the Haihe Laboratory of Sustainable Chemical Transformations for financial support (24HHWCSS00009).

### **Conflict of Interests**

The authors declare no conflict of interest.

#### **Data Availability Statement**

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

**Keywords:** Direct strategy • Hydroxylamine electrosynthesis • Indirect strategy • Reactor engineering

15213773, 0. Downloaded from https://onlinelibrary.wilej.com/doi/10.1002/ainie.202509053 by Tsinghua University Library, Wiley Online Library on [16/6/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/errms-and-conditions) on Wiley Online Library on rules of use; OA arctices are governed by the applicable Creative Commons License

15213773. 0, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/anie.202509053 by Tsinghua University Library, Wiley Online Library on [16/06/2025]. See the Terms

and Conditions (https://onlinelibrary.wiley.com/terms

) on Wiley Online Library for rules of

use; OA

articles are governed by

the applicable Creative Commons License

- GDCh
- J. M. Thomas, R. Raja, Proc. Natl. Acad. Sci. USA 2005, 102, 13732–13736.
- [2] J. Mas-Roselló, T. Smejkal, N. Cramer, Science 2020, 368, 1098– 1102.
- [3] R. Mokaya, M. Poliakoff, Nature 2005, 437, 1243-1244.
- [4] W. L. Semon, J. Am. Chem. Soc. 1923, 45, 188–190.
- [5] R. J. Lewis, K. Ueura, X. Liu, Y. Fukuta, T. E. Davies, D. J. Morgan, L. Chen, J. Qi, J. Singleton, J. K. Edwards, S. J. Freakley, C. J. Kiely, Y. Yamamoto, G. J. Hutchings, *Science* 2022, 376, 615–620.
- [6] P. Roffia, G. Leofanti, A. Cesana, M. Mantegazza, M. Padovan, G. Petrini, S. Tonti, P. Gervasutti, Studies in Surface Science and Catalysis, 1990, 55,43–52. https://doi.org/10.1016/S0167-2991(08) 60132-9
- [7] A. Thangaraj, S. Sivasanker, P. Ratnasamy, J. Catal. 1991, 131, 394–400
- [8] S. Han, H. Li, T. Li, F. Chen, R. Yang, Y. Yu, B. Zhang, *Nat. Catal.* 2023, 6, 402–414.
- [9] Y. Wang, Y. Xu, C. Cheng, B. Zhang, B. Zhang, Y. Yu, Angew. Chem. Int. Ed. 2024, 63, e202315109.
- [10] B. Zhou, Y. Tong, Y. Yao, W. Zhang, G. Zhan, Q. Zheng, W. Hou, X.-K. Gu, L. Zhang, Proc. Natl. Acad. Sci. USA 2024, 121, e2405236121.
- [11] Y. Liu, J. Wei, Z. Yang, L. Zheng, J. Zhao, Z. Song, Y. Zhou, J. Cheng, J. Meng, Z. Geng, J. Zeng, Nat. Commun. 2024, 15, 3619.
- [12] J. Meng, C. Cheng, Y. Wang, Y. Yu, B. Zhang, J. Am. Chem. Soc. 2024, 146, 10044–10051.
- [13] Y. Wang, Y. Qin, W. Li, Y. Wang, L. Zhu, M. Zhao, Y. Yu, Trans. Tianjin Univer. 2023, 29, 275–283.
- [14] V. Rosca, M. Duca, M. T. de Groot, M. T. M. Koper, *Chem. Rev.* 2009, 109, 2209–2244.
- [15] R. Xiang, S. Wang, P. Liao, F. Xie, J. Kang, S. Li, J. Xian, L. Guo, G. Li, Angew. Chem. Int. Ed. 2023, 62, e202312239.

- [16] X. Zhang, H. Jing, S. Chen, B. Liu, L. Yu, J. Xiao, D. Deng, *Chem Catalysis* 2022, 2, 1807–1818.
- [17] Y. Wu, J. Zhao, C. Wang, T. Li, B.-H. Zhao, Z. Song, C. Liu, B. Zhang, Nat. Commun. 2023, 14, 3057.
- [18] Y. Wu, W. Chen, Y. Jiang, Y. Xu, B. Zhou, L. Xu, C. Xie, M. Yang, M. Qiu, D. Wang, Q. Liu, Q. Liu, S. Wang, Y. Zou, *Angew. Chem. Int. Ed.* 2023, 62, e202305491.
- [19] X. Lan, C. Cheng, C. Guo, M. Guo, T. Li, Y. Wu, Y. Yu, B. Zhang, Sci. China: Chem. 2023, 66, 1758–1762.
- [20] J. Sharp, A. Ciotti, H. Andrews, S. R. Udayasurian, M. García-Melchor, T. Li, ACS Catal. 2024, 14, 3287– 3297.
- [21] W. Chen, Y. Wu, Y. Jiang, G. Yang, Y. Li, L. Xu, M. Yang, B. Wu, Y. Pan, Y. Xu, Q. Liu, C. Chen, F. Peng, S. Wang, Y. Zou, J. Am. Chem. Soc. 2024, 146, 6294–6306.
- [22] J. Zhou, S. Han, R. Yang, T. Li, W. Li, Y. Wang, Y. Yu, B. Zhang, Angew. Chem. Int. Ed. 2023, 62, e202305184.
- [23] M. Tursun, C. Wu, Inorg. Chem. 2022, 61, 17448–17458.
- [24] P. Guo, D. Luan, H. Li, L. Li, S. Yang, J. Xiao, J. Am. Chem. Soc. 2024, 146, 13974–13982.
- [25] R. Yang, Y. Wang, H. Li, J. Zhou, Z. Gao, C. Liu, B. Zhang, Angew. Chem. Int. Ed. 2024, 63, e202317167.
- [26] D. H. Kim, S. Ringe, H. Kim, S. Kim, B. Kim, G. Bae, H.-S. Oh, F. Jaouen, W. Kim, H. Kim, C. H. Choi, *Nat. Commun.* 2021, 12, 1856.
- [27] C. Guo, M. Guo, Y. Zhang, S. Han, Y. Yu, J. Am. Chem. Soc. 2025, 147, 14869–14877.
- [28] Y. Wu, Z. Jiang, Z. Lin, Y. Liang, H. Wang, Nat. Sustain. 2021, 4, 725–730.

Manuscript received: April 26, 2025 Revised manuscript received: May 15, 2025 Accepted manuscript online: May 15, 2025 Version of record online:

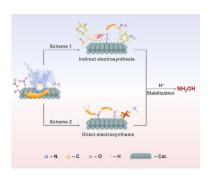
## **Minireview**

## Minireview

### Sustainable Chemistry

Electrochemical Synthesis of Hydroxylamine

This minireview focuses on the indirect and direct electrosynthesis of  $\mathrm{NH}_2\mathrm{OH}$ . The outlook of performance improvement strategies including catalysts and reactor design is also provided.



15213773. 0. Downloaded from https://onlinelbtrary.wiels.com/doi/10.1002/anie.20259935 by Tsinghau University Library, Wiley Online Library on [1606/2025]. See the Terms and Conditions (https://onlinelbtrary.wiels.com/erns-and-conditions) on Wiley Online Library or rules of use; OA articles are governed by the applicable Creative Commons Licenses