

Photoelectrocatalytic Nitrogen Reduction to Ammonia: a Review of Advanced Materials and Interface Engineering

A. Azaizia¹ , N.V. Chirkunova^{1,2} , M. Peng^{3,4} , Y. Tan³ , M.V. Dorogov¹ 

¹ Institute of Advanced Data Transfer Systems, ITMO University, Kronverkskiy pr., 49, lit. A, St. Petersburg, 197198, Russia

² Institute of Advanced Technologies, Togliatti State University, Belorusskaya str. 14, 445667, Togliatti, Russia

³ College of Materials Science and Engineering, State Key Laboratory of Advanced Design and Manufacturing Technology for Vehicle, Hunan University, Changsha, Hunan Province, 410082, China

⁴ Greater Bay Area Institute for Innovation, Hunan University, Guangzhou 511300, Guangdong Province, China

Received: August 28, 2026

Corresponding author: [M.V. Dorogov](mailto:M.V.Dorogov@itmo.ru)

Abstract. Ammonia is essential for fertilizers, chemicals, and emerging carbon-free energy systems, yet its conventional production relies on an energy-intensive process with substantial carbon dioxide emissions. Photoelectrocatalytic nitrogen reduction has emerged as a promising route for sustainable ammonia synthesis under mild conditions, combining solar light absorption with an electrochemical bias to activate the inert nitrogen molecule. This review examines recent progress in this field, focusing on the design of stable titanium dioxide-based photoanodes and selective photocathodes incorporating copper oxide and two-dimensional transition metal dichalcogenides such as molybdenum disulfide and tungsten disulfide. Synthesis strategies, fabrication methods, cell configurations, reaction mechanisms, and performance parameters are discussed. Key challenges, including the high activation barrier of nitrogen, competing hydrogen evolution, and nitrogen mass-transfer limitations, are analyzed alongside verification protocols and future directions for efficient, carbon-free ammonia production.

Acknowledgements. This research was funded by the Ministry of Science and Higher Education of the Russian Federation, project number FSER-2025-0005.

Citation: Rev. Adv. Mater. Technol., 2026, vol. 8, no. 3, pp. 159–175

View online: <https://doi.org/10.17586/2687-0568-2026-8-3-159-175>

View Table of Contents: <https://reviewsamt.com/issues>

REFERENCES

1. S.S.S. Ganti, P.K. Roy, N. Wagh, K.N.S. Siva Sai, S. Kumar. Strategically designed catalysts for ammonia synthesis under mild conditions: recent advances and challenges. *Journal of Materials Chemistry A*, 2025, vol. 13, no. 21, pp. 15361–15426.
2. J.W. Erisman, M.A. Sutton, J. Galloway, Z. Klimont, W. Winiwarter. How a century of ammonia synthesis changed the world. *Nature Geoscience*, 2008, vol. 1, no. 10, pp. 636–639.
3. P. Ganji, R. Zaplotnik, G. Primc, M. Mozetič, A. Vesel. Roles of catalysts in plasma conversion of N_2 and H_2 to NH_3 : Advances, challenges, and future directions. *Energy & Fuels*, 2025, vol. 39, no. 30, pp. 14413–14436.
4. M. Mersch et al. A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States. *Sustainable Energy & Fuels*, 2024, vol. 8, no. 7, pp. 1495–1508.
5. A. Salehabadi, J. Perry, J. Zanganeh, B. Moghtaderi. Emerging perovskite-based catalysts for sustainable and green ammonia production: A promising hydrogen energy carrier. *International Journal of Hydrogen Energy*, 2025, vol. 106, pp. 243–260.
6. Q. Wang et al. Recent advances in ammonia decomposition for hydrogen production: Methods, mechanisms, and trends in photocatalysts and electrocatalysts. *ChemCatChem*, 2025, vol. 17, no. 24, art. no. e01608.
7. Q. Bu et al. Plasma-assisted photo-electrocatalysis in combination with Bi_5O_7I for efficient ammonia synthesis. *Catalysis Science & Technology*, 2025, vol. 15, no. 8, pp. 2617–2627.
8. Y. Fang, Y. Gao, M. Li, Y. Wen, B. Shan. Advances in photoelectrochemical nitrate reduction for solar ammonia synthesis. *Chem Catalysis*, 2026, vol. 6, no. 2, art. no. 101600.
9. M. Arunachalam, J.G. Badiger, S.A. Sayed, S.H. Kang. Photoelectrochemical coupling of waste-nitrogen oxidation reactions with hydrogen evolution for sustainable energy conversion. *ChemSusChem*, 2026, vol. 19, no. 1, art. no. e202501772.
10. C. Han, K. Wang. Recent advances in photoelectrochemical synthesis of nitrogen-containing solar fuels and chemicals. *Energy & Fuels*, 2025, vol. 39, no. 34, pp. 16065–16077.
11. F. Xu et al. Boron doping and high curvature in Bi nanorolls for promoting photoelectrochemical nitrogen fixation. *Applied Catalysis B: Environmental*, 2021, vol. 284, art. no. 119689.
12. Z. Xi, M. Liu. Advancing photoelectrochemical systems for sustainable energy and chemical production: challenges and opportunities. *npj Materials Sustainability*, 2025, vol. 3, no. 1, art. no. 18.
13. L. Wang et al. Photoelectrochemical nitrogen reduction: A step toward achieving sustainable ammonia synthesis. *Chinese Journal of Catalysis*, 2022, vol. 43, no. 7, pp. 1761–1773.
14. D. Ziegenbalg, J. Zander, R. Marschall. Photocatalytic nitrogen reduction: Challenging materials with reaction engineering. *ChemPhotoChem*, 2021, vol. 5, no. 9, pp. 792–807.
15. M. Ismael, M. Wark. A recent review on photochemical and electrochemical nitrogen reduction to ammonia: Strategies to improve NRR selectivity and faradaic efficiency. *Applied Materials Today*, 2024, vol. 39, art. no. 102253.
16. S. Ren et al. Enhanced charge-carrier dynamics and efficient photoelectrochemical nitrate-to-ammonia conversion on antimony sulfide-based photocathodes. *Angewandte Chemie International Edition*, 2024, vol. 63, no. 48, art. no. e202409693.
17. W.J. Dong, Z. Mi. Recent advances in photoelectrochemical ammonia synthesis. *Nano Futures*, 2025, vol. 9, no. 3, art. no. 032002.
18. C. Zuo, Q. Su. Advances in semiconductor-based nanocomposite photo(electro)catalysts for nitrogen reduction to ammonia. *Molecules*, 2023, vol. 28, no. 6, art. no. 2666.

19. M. Li, H. Huang, J. Low, C. Gao, R. Long, Y. Xiong. Recent progress on electrocatalyst and photocatalyst design for nitrogen reduction. *Small Methods*, 2019, vol. 3, no. 6, art. no. 1800388.
20. C.H. Kim, J. Kim, F. Hollmann, C.B. Park. Photoelectrocatalytic N₂ fixation and C-H oxyfunctionalization driven by H₂O oxidation. *Applied Catalysis B: Environmental*, 2023, vol. 336, art. no. 122925.
21. M. Ali et al. Nanostructured photoelectrochemical solar cell for nitrogen reduction using plasmon-enhanced black silicon. *Nature Communications*, 2016, vol. 7, no. 1, art. no. 11335.
22. W.J. Dong et al. Nitrate reduction to ammonia catalyzed by GaN/Si photoelectrodes with metal clusters. *Nature Communications*, 2025, vol. 16, no. 1, art. no. 3383.
23. J.F. Martínez, J. Ohlmann, T. Smolinka, F. Dimroth. Photovoltaic water electrolysis reaching 31.3% solar-to-H₂ conversion efficiency under outdoor operating conditions. *Communications Engineering*, 2026, vol. 5, no. 1, art. no. 78.
24. J. Lu, Y. Lv, S.P. Jiang, J. Zheng. Review on photoelectrochemical nitrogen reduction: advances and perspectives. *Green Chemistry*, 2026, vol. 28, no. 3, pp. 1445–1466.
25. E. Zhao et al. Advancing photoelectrochemical energy conversion through atomic design of catalysts. *Advanced Science*, 2022, vol. 9, no. 1, art. no. 2104363.
26. J. Choi et al. Dichalcogenides as emerging electrocatalysts for efficient ammonia synthesis: A focus on mechanisms and theoretical potentials. *Advanced Functional Materials*, 2025, vol. 35, no. 27, art. no. 2422585.
27. J. Ke et al. Nanocarbon-enhanced 2D photoelectrodes: A new paradigm in photoelectrochemical water splitting. *Nano-Micro Letters*, 2021, vol. 13, no. 1, art. no. 24.
28. C. Jiang, S.J.A. Moniz, A. Wang, T. Zhang, J. Tang. Photoelectrochemical devices for solar water splitting – materials and challenges. *Chemical Society Reviews*, 2017, vol. 46, no. 15, pp. 4645–4660.
29. J. Ma, J. Fu, L. Sun, J. Cheng, J.-F. Li. Photoelectrochemical-driven nitrogen reduction to ammonia by a Vo-SnO₂/TiO₂ composite electrode. *Nanoscale*, 2024, vol. 16, no. 11, pp. 5706–5714.
30. A.A. Mohd Raub, R. Bahru, S.N.A. Mohd Nashruddin, J. Yunas. Advances of nanostructured metal oxide as photoanode in photoelectrochemical (PEC) water splitting application. *Heliyon*, 2024, vol. 10, no. 20, art. no. e39079.
31. M. El Ouardi et al. Review of photoelectrochemical water splitting: From quantitative approaches to effect of sacrificial agents, oxygen vacancies, thermal and magnetic field on (photo)electrolysis. *International Journal of Hydrogen Energy*, 2024, vol. 51, pp. 1044–1067.
32. G.F.C. Mejica et al. Advancements in surface defect-engineered photoelectrocatalysts for enhanced nitrogen reduction to ammonia. *Catalysis Today*, 2026, vol. 476, art. no. 115867.
33. X. Liang, S. Yu, B. Meng, Y. Ju, S. Wang, Y. Wang. Machine-learning-guided design of nanostructured metal oxide photoanodes for photoelectrochemical water splitting: From material discovery to performance optimization. *Nanomaterials*, 2025, vol. 15, no. 12, art. no. 948.
34. X. Xu et al. Morphology-mediated effective spatial charge separation for high-efficiency photoelectrochemical hydrogen production. *Advanced Functional Materials*, 2026, vol. 36, no. 1, art. no. e09250.
35. K. Song et al. Toward efficient utilization of photogenerated charge carriers in photoelectrochemical systems: Engineering strategies from the atomic level to configuration. *Chemical Reviews*, 2024, vol. 124, no. 24, pp. 13660–13680.

36. S. Grushevskaya, I. Belyanskaya, O. Kozaderov. Approaches for modifying oxide-semiconductor materials to increase the efficiency of photocatalytic water splitting. *Materials*, 2022, vol. 15, no. 14, art. no. 4915.
37. M. Nisar, N. Khan, M.I. Qadir, Z. Shah. Recent advances in TiO₂-based photocatalysts for efficient water splitting to hydrogen. *Nanomaterials*, 2025, vol. 15, no. 13, art. no. 984.
38. T.T. Isimjan, S. Rohani, A.K. Ray. Photoelectrochemical water splitting for hydrogen generation on highly ordered TiO₂ nanotubes fabricated by using Ti as cathode. *International Journal of Hydrogen Energy*, 2012, vol. 37, no. 1, pp. 103–108.
39. J. Saïen, Z. Mesgari. Photocatalytic degradation of methyl orange using hematoporphyrin/N-doped TiO₂ nanohybrids under visible light: Kinetics and energy consumption. *Applied Organometallic Chemistry*, 2017, vol. 31, no. 11, art. no. e3755.
40. M. Tayebi, M. Kolaei, A. Tayyebi, Z. Masoumi, Z. Belbasi, B.-K. Lee. Reduced graphene oxide (RGO) on TiO₂ for an improved photoelectrochemical (PEC) and photocatalytic activity. *Solar Energy*, 2019, vol. 190, pp. 185–194.
41. J. Shao et al. In situ synthesis of carbon-doped TiO₂ single-crystal nanorods with a remarkably photocatalytic efficiency. *Applied Catalysis B: Environmental*, 2017, vol. 209, pp. 311–319.
42. P.S. Basavarajappa, S.B. Patil, N. Ganganagappa, K.R. Reddy, A.V. Raghu, Ch.V. Reddy. Recent progress in metal-doped TiO₂, non-metal doped/codoped TiO₂ and TiO₂ nanostructured hybrids for enhanced photocatalysis. *International Journal of Hydrogen Energy*, 2020, vol. 45, no. 13, pp. 7764–7778.
43. A. Robin, M. Bernardes De Almeida Ribeiro, J. Luiz Rosa, R. Zenhei Nakazato, M. Borges Silva. Formation of TiO₂ nanotube layer by anodization of titanium in ethylene glycol-H₂O electrolyte. *Journal of Surface Engineered Materials and Advanced Technology*, 2014, vol. 4, no. 3, pp. 123–130.
44. H.P. Quiroz, F. Quintero, P.J. Arias, A. Dussan, H.R. Zea. Effect of fluoride and water content on the growth of TiO₂ nanotubes synthesized via ethylene glycol with voltage changes during anodizing process. *Journal of Physics: Conference Series*, 2015, vol. 614, art. no. 012001.
45. A. Prathan et al. Controlled structure and growth mechanism behind hydrothermal growth of TiO₂ nanorods. *Scientific Reports*, 2020, vol. 10, no. 1, art. no. 8065.
46. La Ode Asmin, L. Isa. Synthesis and characterization of structural nanocomposite titanium dioxide copper-doped using the impregnation method. *SPEKTRA: Jurnal Fisika dan Aplikasinya*, 2020, vol. 5, no. 1, pp. 21–30.
47. A.H. Bashal, H. Al-Refai, R.M. Ibrahim, A.A. Zaki. Innovatively feasible wet incipient method for preparing Cu doped TiO₂ nanocomposite: Electro-optical measurement supported by quantitative quantum and classical calculations. *Heliyon*, 2024, vol. 10, no. 4, art. no. e25629.
48. X. Li et al. Efficient catalytic fixation nitrogen activity under visible light by molybdenum doped mesoporous TiO₂. *Catalysis Letters*, 2022, vol. 152, no. 1, pp. 116–123.
49. A. Ganesan et al. Electro- and photocatalytic conversion of N₂ to NH₃ by chemically modified transition metal dichalcogenides, MoS₂, and WS₂. *Journal of The Electrochemical Society*, 2023, vol. 170, no. 5, art. no. 056501.
50. L. Ma et al. Two-dimensional transition metal dichalcogenides for electrocatalytic nitrogen fixation to ammonia: Advances, challenges and perspectives. A mini review. *Electrochemistry Communications*, 2021, vol. 125, art. no. 107002.
51. X. Ma et al. N₂ reduction using single transition-metal atom supported on defective WS₂ monolayer as promising catalysts: A DFT study. *Applied Surface Science*, 2019, vol. 489, pp. 684–692.

52. J. Sun et al. Synthesis methods of two-dimensional MoS₂: A brief review. *Crystals*, 2017, vol. 7, no. 7, art. no. 198.
53. R.A. Wells et al. High performance semiconducting nanosheets via a scalable powder-based electrochemical exfoliation technique. *ACS Nano*, 2022, vol. 16, no. 4, pp. 5719–5730.
54. Y. Pi et al. 1T-phase MoS₂ nanosheets on TiO₂ nanorod arrays: 3D photoanode with extraordinary catalytic performance. *ACS Sustainable Chemistry & Engineering*, 2017, vol. 5, no. 6, pp. 5175–5182.
55. D. Chen et al. General synthesis of nanoporous 2D metal compounds with 3D bicontinuous structure. *Advanced Materials*, 2020, vol. 32, no. 46, art. no. 2004055.
56. M. Zhang et al. Hydrothermal synthesis of MoS₂ nanosheet loaded TiO₂ nanoarrays for enhanced visible light photocatalytic applications. *RSC Advances*, 2019, vol. 9, no. 6, pp. 3479–3485.
57. D. Cao et al. Hydrothermal construction of flower-like MoS₂ on TiO₂ NTs for highly efficient environmental remediation and photocatalytic hydrogen evolution. *Separation and Purification Technology*, 2021, vol. 265, art. no. 118463.
58. R. Gopal et al. Facile synthesis and defect optimization of 2D-layered MoS₂ on TiO₂ heterostructure for industrial effluent, wastewater treatments. *Scientific Reports*, 2020, vol. 10, no. 1, art. no. 21625.
59. H. Su, X. Pan, S. Li, H. Zhang, R. Zou. Defect-engineered two-dimensional transition metal dichalcogenides towards electrocatalytic hydrogen evolution reaction. *Carbon Energy*, 2023, vol. 5, no. 6, art. no. e296.
60. H. Fei et al. Targeted modulation of competitive active sites toward nitrogen fixation via sulfur vacancy engineering over MoS₂. *Advanced Functional Materials*, 2023, vol. 33, no. 36, art. no. 2302501.
61. J. Jeon et al. Layer-controlled CVD growth of large-area two-dimensional MoS₂ films. *Nanoscale*, 2015, vol. 7, no. 5, pp. 1688–1695.
62. V. Takhar, R. Banerjee. Emerging photocatalytic applications of transition metal dichalcogenides and hybrid composites for energy applications and environmental remediation. *ChemCatChem*, 2025, vol. 17, no. 13, art. no. e00405.
63. J. Wang, Q. Tian, L. Chen, M. Yang, X. Zhang, X. Wang. TiO₂–Mo₂C heterostructure for enhanced electrocatalytic nitrogen reduction to ammonia. *ACS Omega*, 2024, vol. 9, no. 50, pp. 49945–49952.
64. C. Cheng, T. Shao, X. Tan, X. Li, A.W. Robertson, Z. Sun. Light-driven dinitrogen activation and reduction: from fundamental principles to catalyst design. *Discover Chemistry*, 2026, vol. 3, no. 1, art. no. 13.
65. S.R. Paul, A. Nath, S. Biswas, S.G. Patra. Recent advances in MXene-based electro- and photocatalysts for sustainable nitrogen fixation: A review. *Inorganica Chimica Acta*, 2026, vol. 599, art. no. 123218.
66. D. Liu et al. Development of electrocatalysts for efficient nitrogen reduction reaction under ambient condition. *Advanced Functional Materials*, 2021, vol. 31, no. 11, art. no. 2008983.
67. C. Yang et al. Defect engineering for electrochemical nitrogen reduction reaction to ammonia. *Nano Energy*, 2020, vol. 77, art. no. 105126.
68. M.A. Shipman, M.D. Symes. Recent progress towards the electrosynthesis of ammonia from sustainable resources. *Catalysis Today*, 2017, vol. 286, pp. 57–68.
69. L. Li, C. Tang, H. Jin, K. Davey, S.-Z. Qiao. Main-group elements boost electrochemical nitrogen fixation. *Chem*, 2021, vol. 7, no. 12, pp. 3232–3255.
70. Z. Huang, M. Rafiq, A.R. Woldu, Q.-X. Tong, D. Astruc, L. Hu. Recent progress in electrocatalytic nitrogen reduction to ammonia (NRR). *Coordination Chemistry Reviews*, 2023, vol. 478, art. no. 214981.

71. X. Yang et al. Mechanistic insights into electrochemical nitrogen reduction reaction on vanadium nitride nanoparticles. *Journal of the American Chemical Society*, 2018, vol. 140, no. 41, pp. 13387–13391.
72. Y. Abghoui, E. Skúlason. Electrochemical synthesis of ammonia via Mars-van Krevelen mechanism on the (111) facets of group III–VII transition metal mononitrides. *Catalysis Today*, 2017, vol. 286, pp. 78–84.
73. C. Ling, Y. Zhang, Q. Li, X. Bai, L. Shi, J. Wang. New mechanism for N₂ reduction: The essential role of surface hydrogenation. *Journal of the American Chemical Society*, 2019, vol. 141, no. 45, pp. 18264–18270.
74. D. Chen et al. Boosting protonation kinetics for ammonia electrosynthesis on Ru sites embedded in nanoporous ReSe₂. *Chemical Engineering Journal*, 2023, vol. 475, art. no. 146137.
75. X. Wang, M. Luo, J. Lan, M. Peng, Y. Tan. Nanoporous intermetallic Pd₃Bi for efficient electrochemical nitrogen reduction. *Advanced Materials*, 2021, vol. 33, no. 18, art. no. 2007733.
76. S. Han et al. Controlling activation, selectivity, and transport in photocatalytic N₂ reduction to ammonia. *Coordination Chemistry Reviews*, 2026, vol. 560, art. no. 217884.
77. M. Peng, J. Zhang, J. Ren, Y. Tan. Electronic delocalization engineering of bismuth-based materials for catalytic electrochemical CO₂ and N₂ conversion. *Journal of Materials Chemistry A*, 2024, vol. 12, no. 32, pp. 20638–20654.
78. W. Li et al. Balancing N₂ and H adsorption for electrochemical ammonia synthesis: Mechanisms, operando insights, and design strategies. *Coordination Chemistry Reviews*, 2026, vol. 568, art. no. 218447.
79. A.J. Medford, M.C. Hatzell. Photon-driven nitrogen fixation: Current progress, thermodynamic considerations, and future outlook. *ACS Catalysis*, 2017, vol. 7, no. 4, pp. 2624–2643.
80. W. Zhao, B. Liu, J. Qin, J. Ke, L. Yu, X. Hu. Defect and interface engineering on two-dimensional nanosheets for the photocatalytic nitrogen reduction reaction. *ChemPhotoChem*, 2020, vol. 4, no. 12, pp. 5322–5336.
81. J. Choi, C. Yang, S. Lee, Y.-E. Sung, H.S. Park. Metal sulfide catalysts for selective ammonia production via electrochemical nitrogen reduction. *Meeting Abstracts*, 2025, vol. MA2025-02, no. 53, pp. 2536–2536.
82. A. Hannan, A. Khalil, N. Arshad, M.B. Tahir, A.G. Wattoo, M.K. Shahzad. Transition metal dichalcogenides for photo/electrochemical energy-based applications. *Energy Technology*, 2022, vol. 10, no. 11, art. no. 2200546.
83. Z.H. Ibupoto et al. Advances in MoS₂ composites for electrocatalytic energy conversion: Synthesis, applications, and future perspectives in hydrogen, oxygen, nitrogen, and CO₂ reactions. *Renewable Energy*, 2026, vol. 256, art. no. 124582.
84. M.A. Mushtaq et al. Recent trend in rare earth electrocatalysts for ambient ammonia synthesis: Challenges and perspectives. *Journal of Rare Earths*, 2026, vol. 44, no. 2, pp. 519–537.
85. L. Zhang, Z. Huang, S. Xia. Sc-doped sulfur vacancy MoS₂ photocatalytic nitrogen reduction to ammonia: Experimental and theoretical investigation. *Inorganic Chemistry*, 2025, vol. 64, no. 30, pp. 15736–15747.
86. W. Ye, M. Arif, X. Fang, M.A. Mushtaq, X. Chen, D. Yan. Efficient photoelectrochemical route for the ambient reduction of N₂ to NH₃ based on nanojunctions assembled from MoS₂ nanosheets and TiO₂. *ACS Applied Materials & Interfaces*, 2019, vol. 11, no. 32, pp. 28809–28817.
87. R. Bariki, S.K. Pradhan, S. Panda, S.K. Nayak, A.R. Pati, B.G. Mishra. Hierarchical UiO-66(–NH₂)/CuInS₂ S-scheme photocatalyst with controlled topology for enhanced

- photocatalytic N₂ fixation and H₂O₂ production. *Langmuir*, 2023, vol. 39, no. 22, pp. 7707–7722.
88. T. Bosserez, J. Rongé, J. Van Humbeeck, S. Haussener, J. Martens. Design of compact photoelectrochemical cells for water splitting. *Oil & Gas Science and Technology – Rev. IFP Energies nouvelles*, 2015, vol. 70, no. 5, pp. 877–889.
 89. A. Vilanova, P. Dias, T. Lopes, A. Mendes. The route for commercial photoelectrochemical water splitting: a review of large-area devices and key upscaling challenges. *Chemical Society Reviews*, 2024, vol. 53, no. 5, pp. 2388–2434.
 90. C. Moon, B. Shin. Review on light absorbing materials for unassisted photoelectrochemical water splitting and systematic classifications of device architectures. *Discover Materials*, 2022, vol. 2, no. 1, art. no. 5.
 91. C. Moon, G. Jung, J. Min, B. Shin. Earth-abundant metal oxides for monolithic tandem photoelectrochemical water splitting devices: Current trends and perspectives. *ACS Materials Letters*, 2024, vol. 6, no. 7, pp. 2919–2940.
 92. Gurudayal et al. Perovskite–hematite tandem cells for efficient overall solar driven water splitting. *Nano Letters*, 2015, vol. 15, no. 6, pp. 3833–3839.
 93. L.M. Wilder, K. Balogun, W.E. Klein, P. Chumble, J.L. Young. Nitrogen reduction testing with real-time ¹⁵NH₃ yield quantification using orbital multiturn time-of-flight mass spectrometry. *ACS Energy Letters*, 2024, vol. 9, no. 12, pp. 5780–5786.
 94. R. Liu et al. Incorporating zinc metal sites in aluminum-coordinated porphyrin metal-organic frameworks for enhanced photocatalytic nitrogen reduction to ammonia. *Small*, 2024, vol. 20, no. 44, art. no. 2402779.
 95. T. Ma et al. Interfacial chemical-bonded MoS₂/InBi₂MoO₆ heterostructure for enhanced photocatalytic nitrogen-to-ammonia conversion. *ACS Catalysis*, 2024, vol. 14, no. 8, pp. 6292–6304.
 96. S. Liu et al. Proton-filtering covalent organic frameworks with superior nitrogen penetration flux promote ambient ammonia synthesis. *Nature Catalysis*, 2021, vol. 4, no. 4, pp. 322–331.
 97. J. Nash, X. Yang, J. Anibal, J. Wang, Y. Yan, B. Xu. Electrochemical nitrogen reduction reaction on noble metal catalysts in proton and hydroxide exchange membrane electrolyzers. *Journal of The Electrochemical Society*, 2017, vol. 164, no. 14, pp. F1712–F1716.
 98. C. Ma, N. Zhai, B. Liu, S. Yan. Defected MoS₂: An efficient electrochemical nitrogen reduction catalyst under mild conditions. *Electrochimica Acta*, 2021, vol. 370, art. no. 137695.
 99. Y. Zhao et al. Ammonia detection methods in photocatalytic and electrocatalytic experiments: How to improve the reliability of NH₃ production rates? *Advanced Science*, 2019, vol. 6, no. 8, art. no. 1802109.
 100. S.Z. Andersen et al. A rigorous electrochemical ammonia synthesis protocol with quantitative isotope measurements. *Nature*, 2019, vol. 570, no. 7762, pp. 504–508.
 101. B. Izelaar et al. Revisiting the electrochemical nitrogen reduction on molybdenum and iron carbides: Promising catalysts or false positives? *ACS Catalysis*, 2023, vol. 13, no. 3, pp. 1649–1661.
 102. H.V. Le, T.T.D. Ung, P.D. Tran, H.V. Mai, B.D. Do, L.Q. Nguyen. Enhancing photoelectrocatalytic activity and stability of p-Cu₂O photocathode through n-TiO₂ coating for improved H₂ evolution reaction. *Journal of Physics D: Applied Physics*, 2023, vol. 56, no. 46, art. no. 465502.
 103. P. Wang, X. Wen, R. Amal, Y.H. Ng. Introducing a protective interlayer of TiO₂ in Cu₂O–CuO heterojunction thin film as a highly stable visible light photocathode. *RSC Advances*, 2015, vol. 5, no. 7, pp. 5231–5236.