

铜基复合材料电催化二氧化碳还原制多碳产物的研究进展

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摘要

电催化二氧化碳(CO_2)还原是实现“双碳”目标与碳资源循环利用的核心技术路径, 可将温室气体转化为乙烯、乙醇等高附加值多碳(C_{2+})产物, 兼具环境与经济价值。铜基催化剂因独特电子结构可高效催化C-C耦合反应, 是唯一能定向生成 C_{2+} 产物的金属催化体系, 但纯铜催化剂存在选择性欠佳、稳定性不足的瓶颈。构建铜基复合材料为解决上述问题提供了有效方案: 通过引入杂原子掺杂、金属氧化物等复合组分, 形成 $\text{Cu}^0/\text{Cu}^+/\text{Cu}^{2+}$ 多价态界面, 可协同优化中间体吸附行为、降低C-C偶联能垒, 显著提升催化性能。本文系统综述铜基复合材料的主流构建策略(高温热解、刻蚀、溶剂热、电化学法)及其在电催化 CO_2 还原中的应用优势, 重点剖析其稳定 Cu^+ 活性位点、串联催化富集*CO中间体的核心机制, 为设计开发高效、稳定的铜基复合催化剂提供理论参考与技术启示。

关键词

电催化, 铜基复合材料, 二氧化碳还原

Research Progress in Copper-Based Composites for Electrocatalytic CO_2 Reduction to Multicarbon Products

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Abstract

Electrocatalytic carbon dioxide (CO₂) reduction is a core technical pathway to achieve the “dual carbon” goals and carbon resource recycling, which can convert greenhouse gases into high-value-added multicarbon (C₂₊) products such as ethylene and ethanol, possessing both environmental and economic values. Copper-based catalysts, due to their unique electronic structure, can efficiently catalyze C-C coupling reactions and are the only metal catalytic system capable of selectively producing C₂₊ products. However, pure copper catalysts suffer from drawbacks of poor selectivity and insufficient stability. The construction of copper-based composites provides an effective solution to these issues: by introducing composite components such as heteroatom doping and metal oxides, and forming Cu⁰/Cu⁺/Cu²⁺ multivalent interfaces, it can synergistically optimize the adsorption behavior of intermediates, reduce the energy barrier of C-C coupling, and significantly enhance catalytic performance. This paper systematically summarizes the mainstream construction strategies (high-temperature pyrolysis, etching, solvothermal method, electrochemical method) of copper-based composites and their application advantages in electrocatalytic CO₂ reduction, focusing on analyzing the core mechanisms of stabilizing Cu⁺ active sites and tandem catalysis for enriching *CO intermediates, so as to provide theoretical references and technical insights for the design and development of efficient and stable copper-based composite catalysts.

Keywords

Electrocatalysis, Copper-Based Composites, Carbon Dioxide Reduction

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1. 引言

全球工业化进程中化石能源的过度消耗，导致大气中 CO₂ 浓度持续攀升，温室效应引发的极端气候事件频发，同时化石能源储量枯竭危机催生了可再生能源开发与碳资源化利用技术的创新研发[1][2]。在此背景下，电催化 CO₂ 还原反应(CO₂RR)以太阳能、风能等可再生能源为驱动，可将惰性 CO₂ 分子转化为一氧化碳、甲酸、甲烷及乙烯、乙醇、乙酸等高附加值 C₂₊产物，如图 1 所示，既实现了温室气体的资源化利用，又构建了“碳捕获 - 转化 - 利用”的闭环体系，为达成“双碳”目标提供了关键技术支撑，兼具重要的环境价值与经济前景[3]-[6]。其中，乙烯作为全球产量最大的基础化工原料，传统依赖石油裂解制备，通过 CO₂RR 电催化合成乙烯，可降低对化石资源的依赖，推动化工产业绿色转型。

如图 2 所示，CO₂ 还原过程包含四个关键步骤：抑制析氢反应、促进 CO₂ 吸附与活化、调控一氧化碳(CO)生成与吸附性能、加速 C-C 耦合成键[7]-[9]。在众多 CO₂RR 电催化剂中，铜是唯一对 CO 具有负吸附能且对氢中间体(*H)具有正吸附能的金属，其表面 CO 的中等结合能可在 CO₂ 活化与 CO 转化之间形成平衡，因此铜基催化剂成为目前唯一能高效催化 C-C 耦合反应生成 C₂₊产物的金属催化体系，其催化潜力被广泛认可[10]。铜具有 Cu⁰、Cu⁺、Cu²⁺三种价态，研究表明不同价态主导的催化剂对产物选择性存在显著差异，且混合价态位点中 Cu⁺的占比也会影响产物分布[11]。目前，科研工作者已开发多种策略以提升 C₂₊产物选择性，如铜与第二种金属合金化[12]-[14]、调控铜的氧化态[15]、构建异质结构[16][17]及优化载体材料[18]等。将铜与 MOFs 材料、杂原子掺杂多孔碳材料、氧化物等 CO₂ 捕获材料复合，可

在催化剂表面形成局部高浓度 CO_2 微环境，提升转化效率；与银、金、钯等具有高 CO 选择性的催化剂复合，可提高催化剂表面 CO 覆盖率，形成串联催化效应，促进 C-C 耦合，提升 C_{2+} 产物收率；相较于 Cu^0 或 Cu^{2+} ， Cu^+ 位点被普遍认为具有更低的 C-C 偶联能垒，但 Cu^+ 易被还原，导致催化剂稳定性不足，将铜与可调节电子结构的材料复合可弥补这一缺陷[19]。综上，构建高效铜基复合材料可从多维度提升 C_{2+} 产物的选择性与稳定性，是 CO_2 转化最具潜力的技术路径之一，但在工业化应用中仍面临诸多挑战。

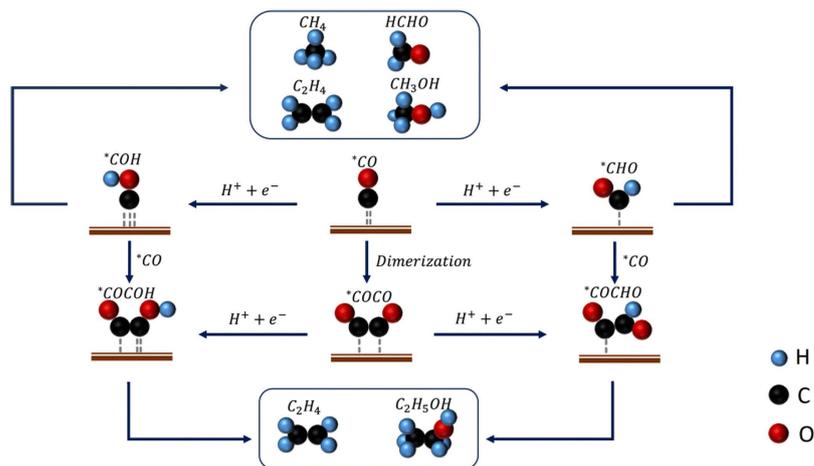


Figure 1. Main electrocatalytic CO_2 reduction pathways on copper-based catalysts
图 1. 铜基催化上主要的电还原二氧化碳路径

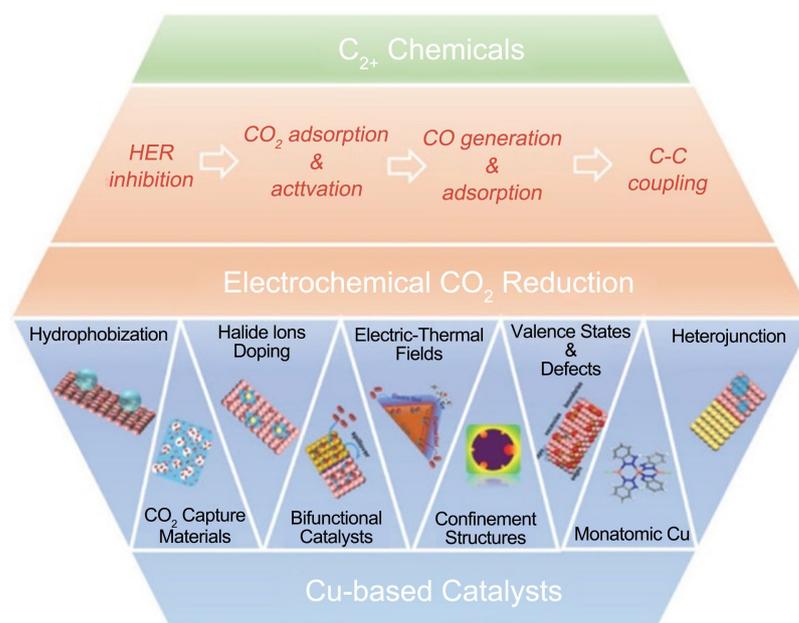


Figure 2. Key steps of electrocatalytic CO_2 reduction
图 2. 电还原二氧化碳的关键步骤

2. 铜基复合材料的构建策略及其在电催化二氧化碳还原中的应用

2.1. 高温热解法

高温热解法通过高温分解金属配合物或金属有机框架(MOFs)，可制备单原子、双原子或合金型铜基

复合材料, 其所用载体(如氮掺杂碳材料)能显著增强催化剂的导电性与结构稳定性。例如, Yang 等人通过煅烧 Cu-BTC 制备了新型 Cu@Cu₂O 电催化剂, 其表面共存的 Cu⁰ 与 Cu⁺形成协同作用, 有效强化了 CO₂ 吸附能力, 促进甲醇生成[20]。Chen 等人设计合成了一系列不同有机连接基的铜基金属氧化物衍生催化剂 X-Cu-BDC (X = NH₂, OH, F, 2F), 其中 2F-Cu-BDC 衍生催化剂对 C₂₊产物的选择性高达 63% [21]。

2.2. 刻蚀策略

刻蚀法以铜合金、铜氧化物等铜基前驱体为基底, 通过酸、碱、配位剂等刻蚀剂选择性去除部分组分, 原位形成多孔结构或异质界面, 其核心优势在于可精准调控材料界面组成, 且刻蚀残留的氧、杂原子等物种可稳定铜活性位点。例如, Tan 等人采用原位化学刻蚀 - 配位聚合耦合策略, 通过时间调控实现 Cu₂O 到 Cu₂O@Cu-MOF 的可控转化, 该催化剂以未完全刻蚀的 Cu₂O 为核, 原位配位聚合形成的 Cu-MOF 为壳层, 显著提升了比表面积与 CO₂ 吸附能力, 核壳协同作用解决了传统铜基催化剂 CO₂ 吸附弱、选择性低、稳定性差的关键问题, 碳氢化合物的法拉第效率高达 79.4% [22]。Sang 等人采用液 - 液界面组装刻蚀策略, 以铜纳米立方体为模板, 通过可控银沉积重构界面结构, 精准合成 CuAg 复合纳米材料, 突破了传统双金属催化剂制备中结构不均、相分离不完全的瓶颈, 实现了对乙烯的高选择性催化[23]。

2.3. 溶剂热法

溶剂热法是一种湿化学策略, 通过在密闭反应容器中以水、乙二醇等为反应介质, 加热形成高温高压环境, 具有简易高效、可避免高温退火导致的颗粒团聚与杂质引入等优势, 可直接获得结晶态催化剂粉末。例如, Feng 等人采用溶剂热法合成不同镱掺杂量的 Yb_γ/CuO_x 催化剂, 将镱均匀掺杂进入 Cu₂O 晶格, 通过晶格压缩促进 Cu₂O 相形成, 实现全 pH 范围、安培级电流密度下高效电催化 CO₂ 还原制 C₂₊产物[24]。Cheng 等人通过溶剂热法设计合成了不同孔径分布与接触角的钷掺杂铜纳米多孔催化剂, 其中 Y@CuO_x-3 催化剂在流动池中表现出 69.19% 的 C₂₊产物法拉第效率[25]。

2.4. 电化学法

电化学法通过调控恒电位、恒电流等电化学信号, 驱动金属源在导电基底上沉积或发生价态转化, 是一种简便低成本的复合材料构建技术, 且制备的电极材料可直接用于电化学还原反应。例如, Yi 等人以铜金属有机框架材料(CuHHTP)为导电基底, 将其涂覆在玻碳电极上, 在 0.1 M KCl/0.1 M KHCO₃ 电解液中施加 -1.2 V vs RHE 恒电位, 经 30 分钟电化学原位还原得到 Cu₂O@CuHHTP 材料; 原位还原过程中, CuHHTP 中部分不稳定的 Cu-O₄ 节点被还原, 生成平均尺寸为 3.5 nm、具有(111)晶面的 Cu₂O 单一类型位点, 剩余 CuHHTP 框架保持完整并作为导电基底, 保障电子从基底向 Cu₂O 活性位点的高效传输; XPS 表征显示, 仅 33% 的 Cu²⁺被还原为 Cu⁺, 无 Cu⁰生成; 且还原过程中 HHTP 配体释放的未配位酚羟基形成富羟基环境, 可与中间体形成氢键, 降低甲烷生成能垒, 使该催化剂在 -1.4 V vs RHE 时对甲烷的选择性高达 73% [26]。Chen 等人通过电沉积法将 Sn 沉积在铜纳米锥表面, 制备 Cu@Sn 纳米锥催化剂, 电沉积在 3.3 mA·cm⁻² 恒电流密度下进行, 通过调控 Sn 沉积时间可显著改变催化剂表面形貌与催化性能[27]。

3. 铜基复合材料应用于电催化二氧化碳还原的优势

3.1. 稳定 Cu⁺价态

Cu⁺是电催化 CO₂ 还原制 C₂₊产物的关键活性位点, 但在负电位下易被还原为 Cu⁰、发生溶出或引发催化剂结构重构, 严重制约催化剂的选择性与稳定性。因此, 稳定 Cu⁺位点是设计高选择性、长耐久性 C₂₊产物催化体系的核心策略。例如, Li 等人通过水热法合成 Cu₂O@CeO_x 核壳结构纳米催化剂, 以 Cu₂O

纳米立方体为核，外层包裹约 1.5 nm 厚的非晶态 CeO_x 壳层，核壳间形成丰富的 Cu/Ce 界面。电还原过程中， CeO_x 壳层可有效抑制 Cu_2O 纳米粒子聚集与结构重构，借助 $\text{Ce}^{4+}/\text{Ce}^{3+}$ 氧化还原循环维持 Cu^+ 价态，同时促进 CO_2 活化与吸附，使该催化剂在大电流密度下 C_{2+} 产物法拉第效率达到 81.8%，且表现出 50 小时的卓越稳定性[28]。Liu 等人合成了 Cu_2O 纳米颗粒与二维 Cu-BDC MOF 组成的异质结构催化剂 ($\text{Cu}_2\text{O}@\text{Cu-BDC}$)，依托二维 Cu-MOF 的 Cu-Cu 配位作用稳定 $\text{Cu}_2\text{O}/\text{Cu-BDC}$ 界面处的 Cu^+ 活性位点，并通过界面优化 *CHO、*COH、*CO 等关键中间体的吸附能，加速 C-C 偶联反应，实现对 C_{2+} 产物的高选择性催化[29]。

3.2. 串联催化富集 *CO 中间体

表面 CO 覆盖率与 C-C 耦合决速步骤密切相关，单一铜金属难以满足 C_{2+} 产物生成的需求，因此引入金、银、钯等第二金属作为助催化剂，构建串联催化体系是提升 CO 覆盖率的有效途径。例如，Wei 等人报道了 $\text{Ag}/\text{Cu}_2\text{O}$ 界面电催化剂，原位拉曼光谱与理论计算证实， $\text{Ag}/\text{Cu}_2\text{O}$ 界面可在部分还原的 Cu^+/Cu^0 活性位点周围实现 CO 高覆盖，同时稳定 Cu^+ 物种，强化 CO 形成与 C-C 耦合[30]。Carlos G. Morales-Guio 等人采用物理气相沉积法制备 Au/Cu 催化剂，该催化剂对醇类产物选择性更高，基于反应机理分析提出串联催化机制：金纳米粒子在铜表面附近将 CO_2 还原为 CO，形成局部高浓度 CO 微环境，促进 *CO 转化为多碳醇类产物[31]。

4. 总结

电催化 CO_2 还原制 C_{2+} 产物是碳资源化利用与“双碳”目标实现的核心路径，铜基复合材料因能精准调控活性位点、优化反应动力学，成为该领域研究热点。本文综述了高温热解、刻蚀、溶剂热及电化学等主流构建策略，其核心优势在于通过稳定 Cu^+ 活性位点、串联催化富集 *CO 中间体，协同提升催化选择性与稳定性。尽管现有研究取得显著进展，但催化剂规模化制备、工业级电流密度下的长效稳定性仍为关键瓶颈。未来需聚焦界面工程与组分精准调控，深化反应机理研究，开发更高效、稳定的铜基复合催化体系，推动其工业化应用。

参考文献

- [1] Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., *et al.* (2012) Global Warming Preceded by Increasing Carbon Dioxide Concentrations during the Last Deglaciation. *Nature*, **484**, 49-54. <https://doi.org/10.1038/nature10915>
- [2] Frank, D.C., Esper, J., Raible, C.C., Büntgen, U., Trouet, V., Stocker, B., *et al.* (2010) Ensemble Reconstruction Constraints on the Global Carbon Cycle Sensitivity to Climate. *Nature*, **463**, 527-530. <https://doi.org/10.1038/nature08769>
- [3] Lee, S.Y., Jung, H., Kim, N.-K., Oh, H.-S., Min, B.K. and Hwang, Y.J. (2018) Mixed Copper States in Anodized Cu Electrocatalyst for Stable and Selective Ethylene Production from CO_2 Reduction. *Journal of the American Chemical Society*, **140**, 8681-8689. <https://doi.org/10.1021/jacs.8b02173>
- [4] García de Arquer, F.P., Dinh, C., Ozden, A., Wicks, J., McCallum, C., Kirmani, A.R., *et al.* (2020) CO_2 Electrolysis to Multicarbon Products at Activities Greater than 1 a Cm^{-2} . *Science*, **367**, 661-666. <https://doi.org/10.1126/science.aay4217>
- [5] Zhang, B., Zhang, J., Hua, M., Wan, Q., Su, Z., Tan, X., *et al.* (2020) Highly Electrocatalytic Ethylene Production from CO_2 on Nanodeficient Cu Nanosheets. *Journal of the American Chemical Society*, **142**, 13606-13613. <https://doi.org/10.1021/jacs.0c06420>
- [6] Wang, L., Li, X., Hao, L., Hong, S., Robertson, A.W. and Sun, Z. (2022) Integration of Ultrafine Cu Nanoparticles with Two-Dimensional Mofs for Enhanced Electrochemical CO_2 Reduction to Ethylene. *Chinese Journal of Catalysis*, **43**, 1049-1057. [https://doi.org/10.1016/s1872-2067\(21\)63947-5](https://doi.org/10.1016/s1872-2067(21)63947-5)
- [7] Wang, Y., Liu, J. and Zheng, G. (2021) Recent Progress in Electrocatalytic CO_2 Reduction to C_{2+} Products on Copper-Based Catalysts. *Adv. Mater.*, **33**, Article No. 2005798.
- [8] Zhou, Y., Liang, Y., Fu, J., Liu, K., Chen, Q., Wang, X., *et al.* (2022) Electrochemical CO_2 Reduction on Copper

- Nanocubes with Controlled Oxide Layers: Role of Oxide Derivation. *Nano Lett.*, **22**, 1963-1970.
- [9] Birdja, Y.Y., Pérez-Gallent, E., Figueiredo, M.C., Göttle, A.J., Calle-Vallejo, F. and Koper, M.T.M. (2019) Advances and Challenges in Understanding the Electrocatalytic Conversion of Carbon Dioxide to Fuels. *Nature Energy*, **4**, 732-745. <https://doi.org/10.1038/s41560-019-0450-y>
- [10] Zhou, X., Shan, J., Chen, L., Xia, B.Y., Ling, T., Duan, J., *et al.* (2022) Stabilizing Cu²⁺ Ions by Solid Solutions to Promote CO₂ Electroreduction to Methane. *Journal of the American Chemical Society*, **144**, 2079-2084. <https://doi.org/10.1021/jacs.1c12212>
- [11] Peng, C., Luo, G., Zhang, J., Chen, M., Wang, Z., Sham, T.-K., *et al.* (2021) Double Sulfur Vacancies by Lithium Tuning Enhance CO₂ Electroreduction to N-Propanol. *Nature Communications*, **12**, Article No. 1580. <https://doi.org/10.1038/s41467-021-21901-1>
- [12] Huang, J., Mensi, M., Oveisi, E., Mantella, V. and Buonsanti, R. (2019) Structural Sensitivities in Bimetallic Catalysts for Electrochemical CO₂ Reduction Revealed by Ag-Cu Nanodimers. *Journal of the American Chemical Society*, **141**, 2490-2499. <https://doi.org/10.1021/jacs.8b12381>
- [13] Chen, C., Li, Y., Yu, S., Louisia, S., Jin, J., Li, M., *et al.* (2020) Cu-ag Tandem Catalysts for High-Rate CO₂ Electrolysis toward Multicarbon. *Joule*, **4**, 1688-1699. <https://doi.org/10.1016/j.joule.2020.07.009>
- [14] Xiong, L., Zhang, X., Yuan, H., Wang, J., Yuan, X., Lian, Y., *et al.* (2020) Breaking the Linear Scaling Relationship by Compositional and Structural Crafting of Ternary Cu-Au/Ag Nanoframes for Electrocatalytic Ethylene Production. *Angewandte Chemie International Edition*, **60**, 2508-2518. <https://doi.org/10.1002/anie.202012631>
- [15] Jung, H., Lee, S.Y., Lee, C.W., Cho, M.K., Won, D.H., Kim, C., *et al.* (2019) Electrochemical Fragmentation of Cu₂O Nanoparticles Enhancing Selective C-C Coupling from CO₂ Reduction Reaction. *Journal of the American Chemical Society*, **141**, 4624-4633. <https://doi.org/10.1021/jacs.8b11237>
- [16] Li, M., Ma, Y., Chen, J., Lawrence, R., Luo, W., Sacchi, M., *et al.* (2021) Residual Chlorine Induced Cationic Active Species on a Porous Copper Electrocatalyst for Highly Stable Electrochemical CO₂ Reduction to C₂₊. *Angewandte Chemie International Edition*, **60**, 11487-11493. <https://doi.org/10.1002/anie.202102606>
- [17] De Gregorio, G.L., Burdyny, T., Loiudice, A., Iyengar, P., Smith, W.A. and Buonsanti, R. (2020) Facet-dependent Selectivity of Cu Catalysts in Electrochemical CO₂ Reduction at Commercially Viable Current Densities. *ACS Catalysis*, **10**, 4854-4862. <https://doi.org/10.1021/acscatal.0c00297>
- [18] Ma, S., Sadakiyo, M., Heima, M., Luo, R., Haasch, R.T., Gold, J.I., *et al.* (2016) Electroreduction of Carbon Dioxide to Hydrocarbons Using Bimetallic Cu-pd Catalysts with Different Mixing Patterns. *Journal of the American Chemical Society*, **139**, 47-50. <https://doi.org/10.1021/jacs.6b10740>
- [19] Yang, H., Li, S. and Xu, Q. (2023) Efficient Strategies for Promoting the Electrochemical Reduction of CO₂ to C₂₊ Products over Cu-Based Catalysts. *Chinese Journal of Catalysis*, **48**, 32-65. [https://doi.org/10.1016/s1872-2067\(23\)64429-8](https://doi.org/10.1016/s1872-2067(23)64429-8)
- [20] Yang, X., Cheng, J., Yang, X., Xu, Y., Sun, W. and Zhou, J. (2022) MOF-Derived Cu@Cu₂O Heterogeneous Electrocatalyst with Moderate Intermediates Adsorption for Highly Selective Reduction of CO₂ to Methanol. *Chemical Engineering Journal*, **431**, 134171. <https://doi.org/10.1016/j.cej.2021.134171>
- [21] Chen, R., Cheng, L., Liu, J., Wang, Y., Ge, W., Xiao, C., *et al.* (2022) Toward High-Performance CO₂-to-C₂ Electroreduction via Linker Tuning on MOF-Derived Catalysts. *Small*, **18**, 2200720. <https://doi.org/10.1002/smll.202200720>
- [22] Tan, X., Yu, C., Zhao, C., Huang, H., Yao, X., Han, X., *et al.* (2019) Restructuring of Cu₂O to Cu₂O@Cu-Metal-Organic Frameworks for Selective Electrochemical Reduction of CO₂. *ACS Applied Materials & Interfaces*, **11**, 9904-9910. <https://doi.org/10.1021/acsami.8b19111>
- [23] Sang, J., Zhang, S., Liu, Q., Geioushy, R.A., Mahmoud, T., Zhang, Y., *et al.* (2025) Liquid-liquid Interface -driven Reconstruction of Cuag Nanocomposites for Selective CO₂ to C₂ H₄ Electroreduction. *Small*, **21**, e08803. <https://doi.org/10.1002/smll.202508803>
- [24] Feng, A., Fang, N., Yuan, X.T., *et al.* (2026) Yb-Doped Cu-Based Catalyst Boosting Electrochemical CO₂-to-C₂₊ Reduction Across pH Range at Ampere-Level Current Density. *Angew. Chem.*, Article No. e10755.
- [25] Cheng, B., Shu, M., Chi, B., Yuan, H., Feng, S., Liu, Z., *et al.* (2025) Enhancing Electroreduction CO₂ to Multi-Carbon Products by the Synergistical Effect of Controllable Pore Size and Local Microenvironment on Y@CuOx Catalysts. *Chemical Engineering Journal*, **515**, 163571. <https://doi.org/10.1016/j.cej.2025.163571>
- [26] Yi, J., Xie, R., Xie, Z., Chai, G., Liu, T., Chen, R., *et al.* (2020) Highly Selective CO₂ Electroreduction to CH₄ by in Situ Generated Cu₂O Single-Type Sites on a Conductive MOF: Stabilizing Key Intermediates with Hydrogen Bonding. *Angewandte Chemie*, **132**, 23849-23856. <https://doi.org/10.1002/ange.202010601>
- [27] Chen, G., Ye, D., Chen, R., Li, J., Zhu, X. and Liao, Q. (2021) Enhanced Efficiency for Carbon Dioxide Electroreduction to Formate by Electrodeposition Sn on Cu Nanowires. *Journal of CO₂ Utilization*, **44**, 101409.

- <https://doi.org/10.1016/j.jcou.2020.101409>
- [28] Li, Y., Zou, J., Sun, L., Liu, S., Li, H., Song, Z., *et al.* (2025) Strong Electronic Interactions of the Abundant Cu/cu Interfaces Stabilized Cu₂O for Efficient CO₂ Electroreduction to C₂₊ Products under Large Current Density. *Advanced Functional Materials*, **35**, 2509899. <https://doi.org/10.1002/adfm.202509899>
- [29] Liu, C., Wang, M., Ye, J., Liu, L., Li, L., Li, Y., *et al.* (2023) Highly Selective CO₂ Electroreduction to C₂₊ Products over Cu₂O-Decorated 2D Metal-Organic Frameworks with Rich Heterogeneous Interfaces. *Nano Letters*, **23**, 1474-1480. <https://doi.org/10.1021/acs.nanolett.2c04911>
- [30] Wei, Z., Wang, W., Shao, T., Yang, S., Liu, C., Si, D., *et al.* (2024) Constructing Ag/Cu₂O Interface for Efficient Neutral CO₂ Electroreduction to C₂H₄. *Angewandte Chemie International Edition*, **64**, e202417066. <https://doi.org/10.1002/anie.202417066>
- [31] Morales-Guio, C.G., Cave, E.R., Nitopi, S.A., Feaster, J.T., Wang, L., Kuhl, K.P., *et al.* (2018) Improved CO₂ Reduction Activity Towards C₂₊ Alcohols on a Tandem Gold on Copper Electrocatalyst. *Nature Catalysis*, **1**, 764-771. <https://doi.org/10.1038/s41929-018-0139-9>