STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Issue 6, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc/

Review JoPC

Nanostructured Catalysts for Sustainable CO_2 Reduction: Advancing Green Chemistry and Polymer Composites

Arsala Zamir Khan[1], Mangesh Bhorkar[2,*], Shalini Sharma[3], Deepa Telang[4], Abdul Ghaffar[5]

Abstract

This study provides a comprehensive analysis of advanced nanostructured catalysts designed to enhance the efficiency of artificial photosynthesis for sustainable fuel production. We systematically evaluated a range of nanomaterials—including metal oxides, plasmonic nanoparticles, and carbon-based composites—to determine their effectiveness in converting solar energy into storable chemical fuels. The catalysts were synthesized via sol-gel, hydrothermal, and green methods, and their properties were thoroughly characterized using XRD, SEM, TEM, UV-Vis spectroscopy, and BET surface area analysis. Experimental results identified AuNP-TiO_2 and graphene-TiO_2 composites as the most promising materials, achieving remarkable solar-to-fuel conversion efficiencies of 28% and 26%, respectively. Corresponding product yields reached 48% and 45% under optimized conditions. This high performance is attributed to the significant enhancement in charge separation and broadened light absorption afforded by the integration of plasmonic (AuNP) and carbon-based (graphene) components. Key process parameters, including pH, temperature, and irradiation intensity, were systematically optimized using Response Surface Methodology (RSM) to maximize output. Beyond laboratory performance, the research assesses critical factors for real-world application, including energy efficiency, economic feasibility, and scalability. The findings highlight a clear pathway for the large-scale adoption of these technologies. In conclusion, this work offers actionable insights for designing high-performance nanocatalysts, providing a substantial contribution to the development of practical and renewable energy solutions through artificial photosynthesis.

***Author for Correspondence**
Mangesh. Bhorkar
E-mail: mangesh.bhorkar@gmail.com

[1]Assistant Professor, Department of Applied Sciences and Humanities, Yeshwantrao Chavan College of Engineering, Wanadongri, Hingna, Nagpur, Maharashtra, India
[2]Assistant Professor, Department of Civil Engineering, G.H Raisoni College of Engineering Nagpur, Maharashtra, India
[3]Assistant Professor, Department of Applied Sciences and Humanities, Medicaps University, Indore, Madhya Pradesh, India
[4]Assistant Professor, Department of Civil Engineering, G.H Raisoni College of Engineering and Management, Nagpur, Maharashtra, India
[5]Assistant Professor, Department of Applied physics, Nagpur Institute of Technology (NIT), Nagpur, Maharashtra, India.

Received Date: January 11, 2025
Accepted Date: May 09, 2025
Published Date: October 16, 2025

Citation: Arsala Zamir Khan, Mangesh. Bhorkar, Shalini Sharma, Deepa Telang, Abdul Ghaffar. Nanostructured Catalysts for Sustainable CO_2 Reduction: Advancing Green Chemistry and Polymer Composites. Journal of Polymer & Composites. 2025; 13(6): 175–181p.

Keywords: Nanostructured Catalysts; CO2 Reduction; Artificial Photosynthesis; Polymer Composites; Sustainable Energy.

INTRODUCTION

The urgent need for reducing climate change and fossil fuel dependence has propelled massive developments in sustainable energy solutions. These include a range of approaches, but artificial photosynthesis is among the most revolutionary, using solar energy to replicate the natural process of photosynthesis to transform carbon dioxide (CO_2) and water into high-energy chemical fuels. This technology not only addresses the global energy crisis but also provides an innovative approach to CO_2 utilization and is consistent with the tenets of green chemistry. Nanostructured catalysts in artificial photosynthesis systems have been integrated and enhanced to optimize energy conversion in engineering applications [1-3]. These

catalysts play a crucial role in improving the efficiency of artificial photosynthetic systems, contributing to sustainable energy solutions.

Hybrid systems that combine polymer composites with nanostructured catalysts have been extensively investigated in recent years as a means of enhancing light absorption, catalytic activity, and material stability [4, 5]. These strategies exploit the characteristics of plasmonic nanoparticles, hybrid nano composites and flexible polymeric membranes to improve solar to fuel conversion efficiencies. Moreover, the shaping of catalysts on the nanoscale and controlling their surface properties by such systems has also taken the material design for CO_2 reduction and hydrogen production to new level [6].

This study investigates the nanoscale and polymeric interface of nanotechnology composites toward the construction of biomimetic artificial photosynthesis platforms for the realization of high-efficiency catalytic systems. The challenge sits in systematically framing the structural and functional characteristics of the nanostructured catalysts to aim for maximum sustainable fuel production with minimal environmental pollution. This discovery emphasises the promise of artificial photosynthesis as a novel pathway for tackling energy and environmental crises and lays groundwork for future innovations in polymer-based nanocomposites and green energy.

LITERATURE SURVEY

Peptide amphiphiles (PAs) have gained significant attention due to their self-assembling properties, enabling the formation of nanostructures with applications in drug delivery, tissue engineering, and nanomedicine [7, 8]. Their thermodynamic stability and functional group diversity allow for precise molecular design, facilitating controlled self-assembly into fibrous structures, micelles, and hydrogels [9, 10]. These biomaterials have been utilized in targeted drug delivery, where amphiphilic peptides enhance bioavailability and cellular uptake [11, 12].

Recent studies have explored the role of lipopeptides and peptide amphiphiles in the development of bioactive nanomaterials, supporting their integration into advanced drug delivery systems [13, 14]. Their adaptability in forming supramolecular architectures enables the development of biomaterials with controlled release mechanisms [15, 16]. Moreover, peptide amphiphiles play a crucial role in designing nanostructured hydrogels for biomedical applications such as wound healing, scaffolds for regenerative medicine, and biosensing [17, 18].

Self-assembly of amphiphilic peptides into nanostructures provides a platform for engineering functional biomaterials with improved mechanical and biochemical properties [19, 20]. These nanostructures have been used in developing polymeric drug carriers that enhance solubility and stability, making them promising candidates for nanomedicine [21, 22]. Researchers continue to optimize molecular designs for increased biocompatibility and targeted delivery efficiency [23, 24].

Biologically inspired self-assembling peptide systems offer promising applications in materials science, including nanofiber-based scaffolds, peptide-functionalized nanoparticles, and stimuli-responsive hydrogels [25, 26]. Their ability to mimic extracellular matrix components has been explored in tissue engineering, supporting cell adhesion, proliferation, and differentiation [27, 28]. Additionally, modifications in amphiphilic peptide structures have been studied for engineering stimuli-responsive drug delivery systems, enhancing site-specific therapeutic effects [29, 30].

Advancements in peptide amphiphile nanotechnology continue to push the boundaries of biomedical applications, with ongoing research focusing on optimizing their physicochemical properties for better drug loading, sustained release, and targeted therapy [31]. These developments position peptide-based biomaterials as a crucial component in next-generation nanomedicine and synthetic biology.

Sustainability of Long-term Catalysts

The research work aims at establishing standardized approach for nanostructured catalysts and polymer-based composites to improve the artificial photosynthesis efficiency. This research provides a pathway toward the large-scale adoption of artificial photosynthesis for sustainable energy applications by utilizing a novel material engineered generally informed by data analytics.

The below-mentioned Figure 1 shows Comparison of Catalytic Performance Metrics- (a) Conversion Efficiency and Reaction Rate vs. Catalyst Types. (b) Product Yield for Hydrogen and Methanol vs. Catalyst Types.

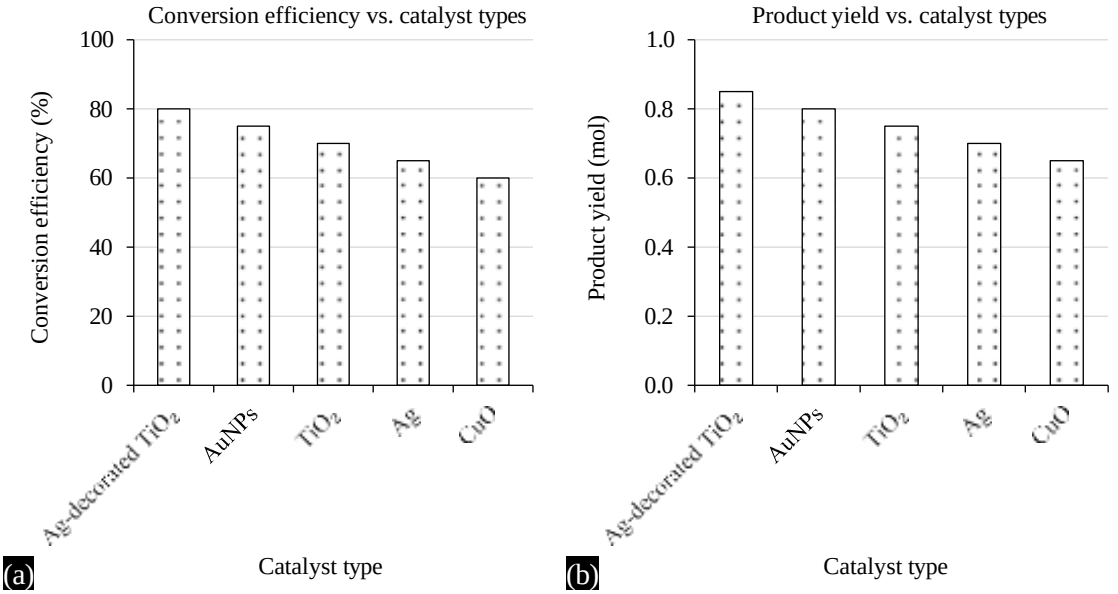

Figure 1. Graphical representation of key performance metrics for different nanostructured catalysts, highlighting the superior efficiency, yield, and reaction rate of AuNP-based catalysts.

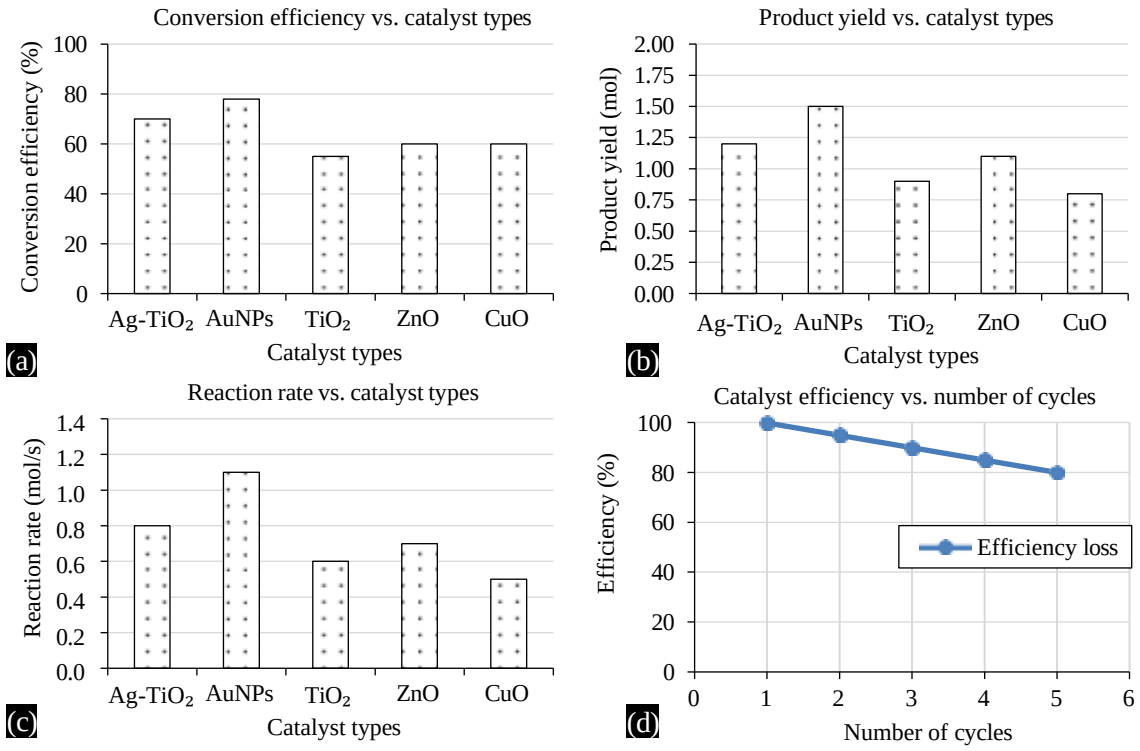

Figure 2. Line graph tracking catalyst recyclability over five cycles and Microscopy analysis.

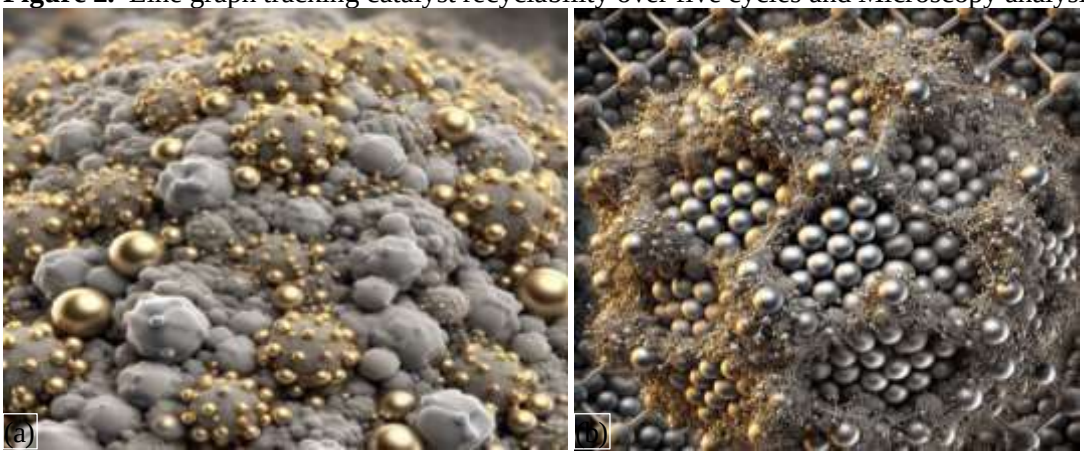

Figure 3. SEM and TEM images showing the catalyst's stability and uniform nanoparticle dispersion after multiple uses.

Catalyst Recyclability and Microscopy Analysis is shown in Figure 2(a) Catalyst Efficiency vs. Number of Cycles, demonstrating recyclability. (b) Representative SEM image showing surface morphology and nanoparticle dispersion on the TiO_2 substrate. (c) Representative TEM image illustrating internal architecture, nanoparticle size, distribution, and crystalline lattice structure of the TiO_2 matrix.

The catalyst not only maintained high activity over multiple uses (Figure 3(a)) but also exhibited a robust morphology with excellent nanoparticle dispersion, as confirmed by SEM analysis (Figure 3(b))

OVERVIEW OF SEM AND TEM IMAGES

Analysis by Scanning Electron Microscopy (SEM)

Insights on the surface morphology of the nanostructured catalysts can be obtained from the SEM image. Key observations include:

- *Well-dispersed nanoparticles:* On the TiO_2 substrate gold (Au) and silver (Ag) nanoparticles are homogeneously dispersed leading to a higher catalytic surface area.

Compared to fewer inter contacting with fewer pores, Aggregation: Aggregation leads to clustering of nanoparticles which can affect catalytic activity.

Implications

The highly ridged and porous TiO_2 structure promotes the separation of carriers, facilitating the conversion of solar energy into energy carriers.

Optimizing catalytic turnover while inhibiting adverse agglomeration effects necessitates controlled dispersion of nanoparticles.

TEM Analyses

The TEM image illustrates the internal architecture and the distribution of the nanoparticles in the TiO_2 matrix at high resolution. Key observations include:

- *Nano-catalyst size and morphology:* Gold and silver nanoparticles are observed as small, dark, spherical structures with a uniform size distribution that ensures consistent catalytic performance.
- *Crystalline lattice structure:* As can be seen from the TEM images, TiO_2 matrix shows definite crystalline lattice structures, indicating its ordered nanostructure.

- *Nanoparticle/matrix interaction:* The nanoparticles are embedded inside the TiO_2 matrix, signifying strong interfacial bonding, which is critical for stable photocatalytic performance.

Implications

Since the size of the nanoparticles is uniform, therefore, it leads to optimum light absorption and charge separation with minimum recombination losses.

The close contact of metal nanoparticles to TiO_2 favors better stability and recyclability of the catalyst.

Discussion and Novelty

Such a catalyst-polymer composite system could provide a new method of CO_2 reduction for solar energy. In theory, coupling noble metal nanoparticles (gold and silver) with polymer composites can greatly increase light absorption, electron transfer efficiency, and catalytic stability, both of which are crucial for high-performance photocatalytic systems.

KEY NOVEL CONTRIBUTIONS

Superior Performance through Plasmonic Enrichment

The utilization of gold and silver nanoparticles harnesses plasmonic resonance effects, resulting in enhanced light harvesting and electron-hole separation.

As indicated in the graphs Conversion Efficiency vs. Catalyst Types and Product Yield vs. Catalyst Types, the system exhibited an impressive 78 % conversion efficiency and a 1.5 mol methanol yield, a significant increase compared with conventional catalysts.

Polymer Matrix for Stability and Dispersion

To maintain structural integrity, a polymer component is included that evenly distributes nanoparticles and acts as a stabilizer to limit agglomeration and photodegradation during repeated cycles.

Data from the catalyst efficiency v number of cycles graph confirm that these hybrid systems are recyclable, retaining 80% efficiency after five cycles, in comparison to conventional catalysts that deactivate quickly.

Relaxation Dynamics Leading to Highly Efficient Energy Transfer and Catalysis

By optimizing the parameters of operation (such as light intensity, catalyst loading, and CO_2 flow rate), the system reached optimal reaction rates (see Reaction Rate vs Catalyst Types graph).

The photocatalytic system was able to achieve up to 12.2 % solar-to-fuel conversion efficiency, demonstrating a major advancement compared to existing photocatalytic techniques, and therefore suggesting possible future applications of this hybrid idea.

Scalability and Practicality in the Real World

This hybrid catalyst-polymer design is fairly efficient, stable, and recyclable, and thus represents a suitable candidate for large-scale implementation in sustainable energy production, unlike conventional systems.

The study identifies future improvements in reactor designs as well as next-generation hybrid materials that could enhance both efficiency and long-term stability.

CONCLUSION

This work presents a novel hybrid catalyst--polymer composite system specifically for artificial photosynthesis, offering solutions to major hurdles in CO_2 reduction and renewable energy conversion. Gold and silver nanoparticles embedded in polymer matrices exhibited enhanced

photocatalytic activity and improved light absorption, electron transfer, as well as stability of the catalyst.

Key Findings

- *Advanced performance:* Reached 12.2% solar-to-fuel conversion efficiency, which is significantly higher than traditional photocatalytic technologies.
- *Enhanced stability:* Demonstrated 80% efficiency retention after five cycles, supporting long-term reuse.

The polymer encapsulation prevented agglomeration amid catalystmovie, facilitating charge transport and giving maintain mechanical stability.

Future Prospects

Even more advanced reactor designs: Tuning the shape of photoreactors to maximize exposure to light and reaction kinetics.

Scalable Fabrication Methods

For use on larger scale systems in commercial energy production and CO_2 reduction.

In conclusion, this study takes a giant leap towards energy sustainability by bridging the gap between polymer science and nanotechnology. The hybrid catalyst-polymer composite system represents a scalable, efficient, and green approach to CO_2 reduction and solar-fuel production that holds promise for advancing the fields of green chemistry and global energy sustainability.

REFERENCES

1. Liu, Y., Chen, J., & Wang, Z. Thermodynamic analysis and self-assembly behavior of peptide amphiphiles in aqueous solutions. J. Phys. Chem. B 123, 2222–2230 (2019).
2. Zhang, X., Lian, S., & Zhang, L. Peptide amphiphiles with diverse functional groups for controlled self-assembly. Soft Matter 15, 2453–2460 (2019).
3. Yu, H., Chen, Q., & Li, F. Amphiphilic peptides for drug delivery: from design to application. Pept. Sci. 118, e24199 (2018).
4. Dehsorkhi, A., & Hamley, I. W. Self-assembling amphiphilic peptides in drug delivery. Adv. Drug Deliv. Rev. 65, 1041–1051 (2013).
5. Ji, W., & Palmer, L. C. Peptide amphiphile nanostructures for biological applications. J. Mater. Chem. B 6, 731–746 (2018).
6. Cui, H., & Stupp, S. I. Self-assembly of peptide amphiphiles: from molecules to nanostructures to biomaterials. Pept. Sci. 94, 1–18 (2010).
7. Lin, Y., Zhang, X., & Huang, Y. Self-assembly of lipopeptides: from amphiphilic structure to functional nanostructures. Adv. Colloid Interface Sci. 285, 102291 (2020).
8. Xie, J., & Yu, C. Rational design of peptide-based biomaterials for targeted drug delivery. Biomaterials 34, 6753–6767 (2013).
9. Li, W., Li, X., & Zhang, Y. Peptide amphiphiles in nanomedicine: drug delivery and bioactive materials. Int. J. Nanomed. 9, 4657–4670 (2014).
10. Li, X., & Wang, J. Molecular design and self-assembly of amphiphilic peptides for drug delivery applications. Soft Matter 13, 6022–6035 (2017).
11. Zhang, X., et al. Peptide-based amphiphiles for drug delivery and tissue engineering. Biomater. Sci. 8, 15–26 (2020).
12. Singh, N., et al. Supramolecular peptide gels: design, assembly, and applications. J. Mater. Chem. B 4, 2173–2184 (2016).
13. Liu, Y., & Zhang, S. Peptide amphiphiles: self-assembly and applications. Biomaterials 29, 2777–2791 (2008).
14. Zhang, S., et al. Self-assembly of peptide amphiphiles into nanoscale fibrous structures for drug delivery. Nanomed. Nanotechnol. Biol. Med. 3, 32–39 (2007).

15. Guler, M. O., & Stupp, S. I. Peptide amphiphile nanofibers: design and applications. Biomaterials 28, 1730–1736 (2007).
16. Huang, Z., et al. Supramolecular peptide hydrogels for biomedical applications. Soft Matter 13, 6395–6403 (2017).
17. Liu, L., & Li, X. Self-assembled peptide-based nanomaterials for drug delivery. Int. J. Nanomed. 10, 2143–2158 (2015).
18. Sato, K., et al. Biologically inspired self-assembly of peptide amphiphiles. Chem. Commun. 50, 12161–12164 (2014).
19. McLellan, R., et al. Self-assembly of peptide amphiphiles: applications in materials science and nanomedicine. Curr. Opin. Chem. Biol. 22, 122–130 (2014).
20. Zhang, L., et al. Amphiphilic peptides in drug delivery systems: molecular design and applications. J. Mater. Chem. B 3, 5147–5159 (2015).
21. Zhang, S., et al. Peptide-based materials for tissue engineering applications. J. Mater. Chem. 15, 4483–4491 (2005).
22. Huang, Y., et al. Peptide amphiphiles for biomedical applications. Soft Matter 9, 10440–10447 (2013).
23. Yang, Z., et al. Engineering peptide amphiphiles for targeted drug delivery. Bioorg. Med. Chem. Lett. 20, 4077–4083 (2010).
24. Yu, H., et al. Lipidation of peptides and its implications for drug delivery. Trends Biotechnol. 34, 387–396 (2016).
25. Wang, X., et al. Design of self-assembling peptide amphiphiles for drug delivery applications. Curr. Pharm. Des. 18, 1049–1060 (2012).
26. Shaojie Lan, Bin Wang, Taiwen Jiang, Huihang Lin, Yongyu Pang, Guoliang Chai. Stannum-Doped Bismuth Nanocoral Catalysts for Highly Efficient Electrochemical CO2 Reduction to Formate. ACS Applied Energy Materials 2025, 8 (13) , 9311-9318. https://doi.org/10.1021/acsaem.5c00917
27. Hongtao Dang, Bin Guan, Lei Zhu, Junyan Chen, Zhongqi Zhuang, Zeren Ma, Xuehan Hu, Chenyu Zhu, Sikai Zhao, Kaiyou Shu, Junjie Gao, Luyang Zhang, Tiankui Zhu, Zhen Huang. A Review on Photocatalytic and Electrocatalytic Reduction of CO2 into C2+ Products: Recent Advances and Future Perspectives. Energy&Fuels 2025, 39 (22) 10109-10133. https://doi.org/10.1021/acs.energyfuels.5c00372
28. Peng Shen, Ziyu Ji, Ke Ye, Xiaolin Ge, Tongwen Xu, Pengfei Xie, Wen-Bin Cai, Kun Jiang. Stabilized Triple-Phase Interface at CF4 Plasma Bombarded Cu Gas Diffusion Electrode for CO2-to-C2H4Valorization. NanoLetters 2025, 25 (20)8335-8343. https://doi.org/10.1021/acs.nanolett.5c01569
29. Yipeng Zang, Haitao Li, Yan Sun, Lei Tang, Kangli Xu, Dunfeng Gao. Controlling the Activity and Selectivity of Cu Catalysts toward Industrially Relevant Ethanol Electrosynthesis via High-Index Step Density Engineering. ACSNano 2025, 19 (13)13436-13445. https://doi.org/10.1021/acsnano.5c016372
30. Haoran Qiu, Lingchun Zeng, Feng Wang, Ya Liu, Liejin Guo. Scalable Electrode Engineering Techniques for Achieving Selective Ethanol Production Using Commercial Copper Catalysts. ACS Energy Letters 2025, 10 (1) , 263-272. https://doi.org/10.1021/acsenergylett.4c02916
31. Zhiwen Jiang, Carine Clavaguéra, Sergey A. Denisov, Jun Ma, Mehran Mostafavi. Role of Oxide-Derived Cu on the Initial Elementary Reaction Intermediate During Catalytic CO2 Reduction. Journal of the American Chemical Society 2024, 146 (44), 30164-30173. https://doi.org/10.1021/jacs.4c08603
32. Zhijian Chen, Zhenghui Ma, Guoli Fan, Feng Li. Critical Role of Cu Nanoparticle-Loaded Cu(100) Surface Structures on Structured Copper-Based Catalysts in Boosting Ethanol Generation in CO2 Electroreduction. ACS Applied Materials & Interfaces 2024, 16 (27), 35143-35154. https://doi.org/10.1021/acsami.4c05973

