

Sustainable Materials and Technology

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Quantum Catalysis Reactions for Sustainability

Catalytic Reaction for Sustainability

 Springer

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ISSN 2731-0426 ISSN 2731-0434 (electronic)
Sustainable Materials and Technology
ISBN 978-981-95-6046-2 ISBN 978-981-95-6047-9 (eBook)
<https://doi.org/10.1007/978-981-95-6047-9>

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Quantum Catalyst Advances in Photoelectrocatalytic CO₂ Reduction Technologies



Abdul Hakeem Anwer, Maroua Saadaoui, Assem T. Mohamed,
Nafees Ahmad, and Abdelbaki Benamor

Abstract Growing population pressures, increasing global energy demand, and the escalating impacts of climate disruption have intensified concerns over future energy security and environmental stability. Solar-driven CO₂ reduction is increasingly recognized as a viable strategy to confront these dual challenges. In this context, photoelectrocatalysis provides a particularly attractive approach, as it merges light harvesting with electrochemical control, enabling efficient solar energy conversion under mild reaction conditions while avoiding the need for extreme temperatures or high applied voltages. This combined strategy holds significant promise for achieving efficient and selective CO₂ conversion. The chapter provides an overview of the fundamental principles underlying photocatalytic, electrocatalytic, and photoelectrocatalytic CO₂ reduction, emphasizing their distinctive operational characteristics. Different photoelectrocatalytic configurations are described and evaluated in a comparative framework. Particular attention is given to factors that govern performance, such as the interaction between catalysts and reactant molecules, operating conditions, and the physicochemical properties of photoelectrodes. Advances in mechanistic understanding and approaches for enhancing activity including the optimization of light harvesting, suppression of charge recombination, and acceleration of surface reaction dynamics are critically examined. The discussion concludes with an assessment of current limitations and potential future directions for the development of photoelectrocatalytic CO₂ reduction technologies.

Keywords Photo electrocatalytic · CO₂ reduction · Quantum catalyst · Electrocatalyst

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References

1. Anwer AH et al (2023) Simultaneous reduction of carbon dioxide and energy harvesting using RGO-based SiO₂-TiO₂ nanocomposite for supercapacitor and microbial electrosynthesis. *Appl Catal B* 339:123091
2. Birdja YY et al (2019) Advances and challenges in understanding the electrocatalytic conversion of carbon dioxide to fuels. *Nat Energy* 4(9):732–745
3. Song RB et al (2020) Electrode materials engineering in electrocatalytic CO₂ reduction: energy input and conversion efficiency. *Adv Mater* 32(27):1903796
4. Xie S et al (2016) Photocatalytic and photoelectrocatalytic reduction of CO₂ using heterogeneous catalysts with controlled nanostructures. *Chem Commun* 52(1):35–59
5. Wu HL et al (2019) Semiconductor quantum dots: an emerging candidate for CO₂ photoreduction. *Adv Mater* 31(36):1900709
6. Shit SC et al (2020) Integrated nano-architected photocatalysts for photochemical CO₂ reduction. *Nanoscale* 12(46):23301–23332
7. Zhou Y et al (2021) Engineering 2D photocatalysts toward carbon dioxide reduction. *Adv Energy Mater* 11(8):2003159
8. Wang P et al (2018) Recent progress on photo-electrocatalytic reduction of carbon dioxide. *Part Part Syst Charact* 35(1):1700371
9. Ješić D et al (2021) Engineering photocatalytic and photoelectrocatalytic CO₂ reduction reactions: mechanisms, intrinsic kinetics, mass transfer resistances, reactors and multi-scale modelling simulations. *Chem Eng J* 407:126799
10. Chen P et al (2021) Photoelectrocatalytic carbon dioxide reduction: fundamental, advances and challenges. *Nano Mater Sci* 3(4):344–367
11. Kumaravel V, Bartlett J, Pillai SC (2020) Photoelectrochemical conversion of carbon dioxide (CO₂) into fuels and value-added products. *ACS Energy Lett* 5(2):486–519
12. Park YH et al (2021) Recent advances in quantum dots for photocatalytic CO₂ reduction: a mini-review. *Front Chem* 9:734108
13. Cao F et al (2018) A layer-by-layer growth strategy for large-size InP/ZnSe/ZnS core-shell quantum dots enabling high-efficiency light-emitting diodes. *Chem Mater* 30(21):8002–8007
14. Salunkhe TT et al (2023) Recent innovative progress of metal oxide quantum-dot-integrated g-C₃N₄ (0D–2D) synergistic nanocomposites for photocatalytic applications. *Catalysts* 13(11):1414
15. Lingampalli S, Ayyub MM, Rao C (2017) Recent progress in the photocatalytic reduction of carbon dioxide. *ACS Omega* 2(6):2740–2748
16. Zhang B, Sun L (2019) Artificial photosynthesis: opportunities and challenges of molecular catalysts. *Chem Soc Rev* 48(7):2216–2264
17. Wang X et al (2021) CsPbBr₃ perovskite nanocrystals anchoring on monolayer MoS₂ nanosheets for efficient photocatalytic CO₂ reduction. *Chem Eng J* 416:128077
18. Jiang Z et al (2019) Living atomically dispersed Cu ultrathin TiO₂ nanosheet CO₂ reduction photocatalyst. *Adv Sci* 6(15):1900289
19. Zhou B et al (2018) Mo–Bi–Cd ternary metal chalcogenides: highly efficient photocatalyst for CO₂ reduction to formic acid under visible light. *ACS Sustain Chem Eng* 6(5):5754–5759
20. AlOtaibi B et al (2015) Wafer-level artificial photosynthesis for CO₂ reduction into CH₄ and CO using GaN nanowires. *ACS Catal* 5(9):5342–5348
21. Barton EE, Rampulla DM, Bocarsly AB (2008) Selective solar-driven reduction of CO₂ to methanol using a catalyzed p-GaP based photoelectrochemical cell. *J Am Chem Soc* 130(20):6342–6344
22. Zhao Y et al (2015) Defect-rich ultrathin ZnAl-layered double hydroxide nanosheets for efficient photoreduction of CO₂ to CO with water. *Adv Mater* 27(47):7824–7831
23. Luo J et al (2019) A critical review on energy conversion and environmental remediation of photocatalysts with remodeling crystal lattice, surface, and interface. *ACS Nano* 13(9):9811–9840