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Review

Dual-Metal Catalysts in Electrochemical Carbon Dioxide Conversion

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Abstract: The escalating atmospheric carbon dioxide concentration has intensified the urgency for developing efficient carbon dioxide conversion technologies. Electrochemical carbon dioxide reduction represents a promising approach to convert carbon dioxide into valuable chemicals and fuels while utilizing renewable electricity. Dual-metal catalysts have emerged as a breakthrough strategy, offering synergistic effects that surpass the limitations of single-metal catalysts. These bimetallic systems demonstrate enhanced catalytic activity, improved product selectivity, and superior stability through electronic modification, geometric arrangement, and cooperative catalytic mechanisms. This paper comprehensively examines recent developments in dual-metal catalysts for electrochemical carbon dioxide conversion, focusing on copper-based bimetallic combinations including copper-palladium, copper-bismuth, and copper-zinc systems. The discussion encompasses mechanistic insights, synthetic strategies, structure-activity relationships, and performance optimization approaches. By analyzing various bimetallic configurations and their catalytic behaviors, this work highlights critical factors governing product distribution and conversion efficiency. The findings underscore the potential of dual-metal catalysts in advancing sustainable carbon dioxide utilization technologies toward industrial implementation.

Keywords: dual-metal catalysts; carbon dioxide reduction; electrochemical conversion; bimetallic systems; copper catalysts; synergistic effects

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1. Introduction

The anthropogenic emission of carbon dioxide has reached unprecedented levels, contributing significantly to global climate change and environmental degradation. Converting carbon dioxide into valuable chemicals and fuels through electrochemical reduction represents a dual-benefit strategy that simultaneously addresses climate concerns and energy storage challenges. The electrochemical carbon dioxide reduction reaction offers the advantage of operating under ambient conditions while utilizing renewable electricity sources, making it an attractive pathway for sustainable chemical production [1]. However, the inherent stability of the carbon dioxide molecule and the complexity of multi-electron transfer processes pose substantial challenges in achieving high conversion efficiency and product selectivity. Traditional single-metal catalysts often suffer from limited activity, poor selectivity toward desired products, and competing hydrogen evolution reactions that reduce overall efficiency.

The development of dual-metal catalysts has emerged as a transformative approach to overcome these fundamental limitations. Bimetallic systems introduce synergistic effects through electronic interactions between different metal centers, geometric arrangements that create unique active sites, and cooperative mechanisms that facilitate complex reaction pathways [2]. These catalysts can be engineered to optimize the binding energies of reaction intermediates, lower activation barriers, and direct reaction pathways toward specific products. The strategic combination of two metals allows for fine-tuning of catalytic properties that cannot be achieved with monometallic systems. Copper-based bimetallic catalysts have received particular attention due to copper's unique ability to reduce carbon dioxide beyond carbon monoxide to hydrocarbon and oxygenate products [3, 4]. When paired with secondary metals such as palladium, bismuth, zinc, or other transition metals, copper-based systems demonstrate remarkable improvements in both activity and selectivity.

The rational design of dual-metal catalysts requires understanding the fundamental principles governing metal-metal interactions and their influence on catalytic performance. Electronic effects arise from charge transfer between metals, modifying the d-band center and altering adsorption energies of key intermediates. Geometric effects result from the spatial arrangement of metal atoms, creating distinct active sites with specific coordination environments [5, 6]. The interplay between these factors determines the catalyst's ability to stabilize transition states, facilitate proton-coupled electron transfer, and promote carbon-carbon coupling reactions. Recent advances in synthetic methodologies have enabled precise control over bimetallic catalyst architectures, including phase-separated structures, core-shell configurations, and atomically dispersed dual-site arrangements [7, 8]. Each architectural motif exhibits distinct catalytic behaviors and product distributions, highlighting the importance of structure-performance relationships in catalyst design.

2. Fundamental Principles of Dual-Metal Catalysis

2.1. Electronic and Geometric Effects in Bimetallic Systems

The superior performance of dual-metal catalysts stems from fundamental electronic and geometric modifications that distinguish them from their monometallic counterparts. Electronic effects in bimetallic systems manifest through charge redistribution and d-band center shifts, which directly influence the adsorption strength of reaction intermediates on the catalyst surface. When two metals with different electronegativities are brought into intimate contact, electrons transfer from the less electronegative metal to the more electronegative one, creating electron-rich and electron-deficient regions [9]. This charge redistribution modifies the local electronic structure and alters the binding energies of key species such as carbon dioxide, carbon monoxide, and various carbon-containing intermediates. The d-band center theory provides a framework for understanding these electronic modifications, as shifts in the d-band position relative to the Fermi level correlate with changes in adsorption energies and catalytic activity.

Geometric effects arise from the spatial arrangement of atoms in bimetallic catalysts and contribute significantly to their catalytic properties. The introduction of a secondary metal can create strain in the crystal lattice, modify interatomic distances, and generate unique coordination environments that serve as active sites [10]. These geometric modifications influence the catalyst's ability to stabilize specific reaction intermediates and transition states. In copper-based bimetallic systems, the secondary metal can disrupt the continuous copper surface, creating isolated copper sites or copper ensembles with distinct geometries. Such structural modifications prove crucial for suppressing unwanted side reactions while promoting desired product formation. The combination of electronic and geometric effects results in synergistic behaviors where the overall catalytic performance exceeds the sum of individual metal contributions [11].

The synergistic effects in dual-metal catalysts extend beyond simple electronic and geometric considerations to encompass cooperative catalytic mechanisms. In tandem catalysis, different metal sites perform distinct roles in the overall reaction sequence, with one metal activating carbon dioxide and another facilitating subsequent transformation steps [12]. This division of labor allows each metal to operate in its optimal regime, enhancing overall efficiency. The proximity of different metal sites becomes critical in tandem mechanisms, as intermediate species must transfer efficiently between sites without desorbing into solution. Understanding these cooperative effects requires comprehensive mechanistic studies combining experimental observations with theoretical calculations. Density functional theory calculations have proven invaluable in elucidating the energy landscapes of bimetallic catalysts, revealing how metal-metal interactions modify reaction pathways and influence product selectivity [13]. Table 1 summarizes key electronic and geometric effects observed in representative dual-metal catalyst systems.

Table 1. Electronic and Geometric Effects in Dual-Metal Catalysts.

Metal Combination	Electronic Effect	Geometric Effect	Synergistic Mechanism	Major Product
Cu-Pd	Charge transfer to Pd	Modified Cu ensemble	Tandem activation	C2+ hydrocarbons
Cu-Bi	Electron enrichment	Isolated Cu sites	CO stabilization	Formate
Cu-Zn	d-band modulation	Lattice strain	CO adsorption control	Ethylene
Cu-Ag	Electronic perturbation	Surface reconstruction	CO dimerization	Ethylene

2.2. Mechanistic Pathways and Reaction Intermediates

The mechanistic complexity of electrochemical carbon dioxide reduction on dual-metal catalysts involves multiple electron transfer steps and various possible intermediates, leading to diverse product distributions. The reaction initiates with carbon dioxide adsorption on the catalyst surface, followed by the first electron transfer to form a carbon dioxide radical anion intermediate. This initial step represents a kinetic bottleneck due to the high energy required to activate the stable carbon dioxide molecule [13]. Bimetallic catalysts can lower this activation barrier through electronic modifications that stabilize the radical anion intermediate. The subsequent reaction pathway depends on the catalyst composition, surface structure, and applied potential, with different routes leading to carbon monoxide, formate, methanol, ethylene, or other products.

The divergence in mechanistic pathways becomes particularly evident when comparing pathways to one-carbon versus two-carbon products. Formation of carbon monoxide involves relatively straightforward reduction without carbon-carbon bond formation, making it kinetically favorable on many catalysts. However, achieving carbon-carbon coupling to produce valuable multi-carbon products requires precise control over intermediate stabilization and surface coverage [14]. Dual-metal catalysts can facilitate carbon-carbon coupling through several mechanisms including carbon monoxide dimerization, carbene coupling, or ketene pathways. The secondary metal in bimetallic systems can modify the binding strength of carbon monoxide intermediates, maintaining optimal surface coverage that promotes coupling while preventing catalyst poisoning.

Proton-coupled electron transfer processes play a crucial role in determining product selectivity and overall reaction efficiency. The source of protons, whether from water molecules or hydronium ions, influences the reaction kinetics and thermodynamics [15]. Dual-metal catalysts can modulate the local proton availability through electronic effects that alter water adsorption and dissociation behaviors. The competing hydrogen evolution reaction represents a major challenge in electrochemical carbon dioxide reduction, as both processes involve similar potential ranges and mechanistic steps. Bimetallic systems can suppress hydrogen evolution by optimizing the hydrogen binding energy, making carbon dioxide reduction thermodynamically and kinetically more favorable. Table 2 presents mechanistic pathways and key intermediates involved in carbon dioxide reduction to various products.

Table 2. Mechanistic Pathways for CO2 Reduction Products.

Product	Initial Intermediate	Critical Step	Metal Function	Electron Steps
CO	COOH radical	First electron transfer	CO2 activation	2 electrons
HCOOH	OCHO intermediate	Formate formation	Moderate binding	2 electrons
CH3OH	CHO intermediate	C-OH formation	Sequential reduction	6 electrons
C2H4	CO dimer	C-C coupling	Dimerization site	12 electrons
C2H5OH	COCO intermediate	Asymmetric reduction	Tandem mechanism	12 electrons

2.3. Structure-Activity Relationships

The relationship between catalyst structure and catalytic activity constitutes a central theme in dual-metal catalyst design, as subtle changes in composition and architecture can dramatically affect performance. Phase-separated bimetallic catalysts, where the two metals exist as distinct domains, exhibit different catalytic behaviors compared to alloyed or core-shell structures. In phase-separated configurations, each metal retains its intrinsic properties while interfacial sites provide unique catalytic environments [1]. These interfaces often serve as the most active sites due to the combined electronic and geometric effects at the metal-metal boundary. The width and nature of these interfacial regions can be controlled through synthetic parameters, allowing for optimization of active site density and distribution.

Core-shell bimetallic catalysts feature one metal completely encapsulating another, creating a structure where the shell metal dominates surface chemistry while the core metal provides electronic perturbations through subsurface interactions [2]. This architecture allows for efficient utilization of expensive noble metals by placing them in the shell layer while using abundant metals as the core. The electronic interaction between core and shell metals can extend several atomic layers, influencing the shell's catalytic properties without direct exposure of the core metal to reactants. Strain effects induced by lattice mismatch between core and shell metals further modify surface reactivity.

Atomically dispersed dual-site catalysts represent an emerging frontier in bimetallic catalyst design, where two different metal atoms are isolated and precisely positioned at defined distances. These catalysts maximize metal utilization efficiency and create well-defined active sites with uniform catalytic properties [11]. The spacing between metal atoms in dual-atom catalysts determines whether they function independently or cooperatively in the catalytic cycle. Theoretical studies have shown that optimal metal-metal distances exist for different products, with closer spacings favoring carbon-carbon coupling reactions and larger separations promoting independent one-carbon product formation [13]. The support material plays a crucial role in stabilizing dual-atom configurations, with nitrogen-doped carbon, metal-organic frameworks, and oxide supports providing coordination environments that prevent metal aggregation.

3. Copper-Based Dual-Metal Catalyst Systems

3.1. Copper-Palladium Bimetallic Catalysts

Copper-palladium bimetallic catalysts represent one of the most extensively studied systems for electrochemical carbon dioxide reduction, combining copper's unique ability to produce hydrocarbons with palladium's excellent carbon dioxide activation properties. The synergy between these metals arises from complementary electronic structures and catalytic functions, where palladium facilitates initial carbon dioxide activation and carbon monoxide formation, while copper promotes subsequent reduction and carbon-carbon coupling steps [4]. This tandem mechanism enables efficient conversion of carbon dioxide to multi-carbon products including ethylene, ethanol, and propanol. The distribution and arrangement of copper and palladium atoms significantly influence the product distribution, with phase-separated structures favoring different products compared to alloyed configurations.

In copper-palladium systems, the palladium component modifies the electronic structure of adjacent copper sites through charge transfer and d-band center shifts. Experimental studies combined with density functional theory calculations reveal that palladium enriches electron density on neighboring copper atoms, strengthening carbon monoxide binding and facilitating carbon-carbon coupling reactions [4]. The optimal palladium content typically ranges from five to twenty atomic percent, as excessive palladium leads to surface coverage that blocks copper active sites and promotes hydrogen evolution. Spatial distribution patterns also matter, with clustered palladium atoms providing carbon monoxide spillover sites while isolated palladium atoms offer single-site activation centers.

The catalytic performance of copper-palladium bimetallic systems demonstrates remarkable improvements over monometallic copper in both activity and selectivity toward two-carbon products. Faradaic efficiencies exceeding seventy percent for ethylene have been reported on optimized copper-palladium catalysts, compared to typically forty to fifty percent on pure copper under similar conditions [4]. The current density also increases substantially, indicating enhanced reaction kinetics resulting from the bimetallic synergy. Long-term stability tests reveal that copper-palladium catalysts maintain their performance over extended electrolysis periods, with minimal degradation in selectivity or activity. Table 3 summarizes performance characteristics of various copper-palladium catalyst configurations.

Table 3. Performance of Copper-Palladium Catalysts.

Configuration	Pd Content	Product	Faradaic Efficiency	Current Density	Potential
Phase-separated	10 at%	C2H4	68%	180 mA/cm²	-1.0 V
Alloyed	15 at%	C2H4	72%	210 mA/cm²	-1.05 V
Core-shell	8 at%	C2H5OH	45%	150 mA/cm²	-0.95 V
Pd-modified	5 at%	C2+	65%	165 mA/cm²	-1.0 V

3.2. Copper-Bismuth Systems

Copper-bismuth bimetallic catalysts offer a distinct approach to electrochemical carbon dioxide reduction, where bismuth serves primarily to modify copper's electronic properties and geometric structure rather than directly participating in catalysis. Bismuth has a strong tendency to produce formate from carbon dioxide reduction due to its favorable binding geometry for the formate intermediate [6]. When combined with copper, bismuth atoms act as site isolators that break up continuous copper surfaces into smaller ensembles and isolated sites. This geometric modification suppresses pathways requiring large copper ensembles, such as methane formation, while promoting reactions that can occur on smaller copper clusters.

The synthesis of copper-bismuth catalysts typically involves electrodeposition or co-reduction methods that allow control over bismuth distribution and surface coverage. Studies have shown that bismuth preferentially occupies grain boundaries and surface defect sites, creating a heterogeneous distribution that generates diverse active sites [6]. This non-uniform distribution proves beneficial for catalytic performance, as it provides a spectrum of sites with varying copper ensemble sizes and electronic properties. The bismuth content must be carefully optimized, as excessive bismuth coverage blocks copper sites and shifts product distribution toward formate at the expense of more valuable carbon-carbon coupled products. Optimal bismuth contents typically range from five to fifteen atomic percent, achieving a balance between geometric modification and active site preservation. Table 4 presents performance metrics of copper-bismuth catalysts at different bismuth loadings.

Table 4. Copper-Bismuth Catalyst Performance.

Bi Content	Primary Product	Faradaic Efficiency	Current Density	Selectivity Mechanism
5 at%	CO/$HCOO^-$	60%	140 mA/cm²	Electronic modification
10 at%	$HCOO^-$	75%	165 mA/cm²	Site isolation
15 at%	$HCOO^-$	70%	150 mA/cm²	Ensemble control
20 at%	$HCOO^-$	68%	130 mA/cm²	Surface blocking

3.3. Copper-Zinc Intermetallic Catalysts

Copper-zinc bimetallic catalysts have gained significant attention for their ability to enhance selectivity toward two-carbon products through favorable modification of carbon monoxide binding energies. Zinc influences copper's catalytic properties through both electronic effects and the formation of brass-like intermetallic phases [7, 8]. The incorporation of zinc into copper lattices creates compressive strain that modifies the copper d-band center, optimizing the binding strength of key intermediates. Additionally, zinc can alter the local pH environment near the catalyst surface by influencing water dissociation and proton availability. This pH modulation affects the concentration of carbonate and bicarbonate species, which play roles in carbon dioxide transport and buffer capacity.

Electrodeposition techniques enable the synthesis of copper-zinc catalysts with controlled phase composition, producing either phase-separated structures or intermetallic compounds depending on synthesis parameters [7]. The catalytic performance of copper-zinc systems demonstrates enhanced carbon-carbon coupling efficiency compared to pure copper, with ethylene and ethanol as major products. The optimal zinc content varies depending on the desired product, with moderate zinc concentrations favoring ethylene while higher zinc contents promote ethanol formation [8]. Current densities on copper-zinc catalysts remain comparable to or exceed those on pure copper, indicating that activity is maintained while selectivity improves. Stability studies reveal that copper-zinc intermetallic phases exhibit superior resistance to restructuring compared to pure copper or phase-separated mixtures, maintaining consistent performance over hundreds of hours of operation. The enhanced stability arises from stronger metal-metal bonding in intermetallic compounds and reduced susceptibility to oxidation-reduction cycling. Table 5 compares structural characteristics and performance of different copper-zinc phases.

Table 5. Copper-Zinc Catalyst Structures and Performance.

Structure Type	Zn Content	Major Product	Faradaic Efficiency	Stability	Mechanism
Phase-separated	15 at%	C_2H_4	65%	150 hours	CO binding optimization
Brass phase	25 at%	C_2H_5OH	52%	180 hours	Strain effect
Intermetallic	30 at%	C2+ mixed	58%	200 hours	pH modulation
Cu-rich alloy	10 at%	C_2H_4	62%	120 hours	Electronic perturbation

4. Synthetic Strategies and Catalyst Engineering

4.1. Electrochemical Deposition Methods

Electrochemical deposition stands as one of the most versatile and controllable methods for synthesizing dual-metal catalysts, offering precise control over composition, morphology, and structure through manipulation of deposition parameters. This technique involves the electrochemical reduction of metal precursors dissolved in an electrolyte solution onto a conductive substrate, with the deposition occurring when the applied potential becomes sufficiently negative to reduce the metal ions [7]. For bimetallic systems, two approaches exist including simultaneous co-deposition of both metals from a mixed precursor solution, or sequential deposition where one metal is deposited first followed by the second metal.

The advantages of electrochemical deposition include room-temperature operation, scalability to large surface areas, and the ability to deposit materials into complex geometries and porous structures. The morphology of electrodeposited catalysts can be controlled through deposition current density, with low current densities generally producing compact, smooth films and high current densities yielding porous, dendritic structures [7]. Pulse deposition techniques, where the current or potential is cycled between deposition and rest periods, enable better control over crystal nucleation and growth, often producing more uniform particle distributions and refined microstructures. For copper-zinc catalysts, electrodeposition has proven particularly effective in generating intermetallic phases by controlling the deposition sequence and subsequent thermal treatment [8].

4.2. Chemical Reduction and Thermal Treatment

Wet chemical synthesis methods including co-reduction, sol-gel processes, and colloidal synthesis offer complementary approaches to electrodeposition for producing dual-metal catalysts. Co-reduction involves simultaneous reduction of two metal precursors in solution using chemical reducing agents such as sodium borohydride, hydrazine, or hydrogen gas [10]. The reduction kinetics of different metal ions can be matched through appropriate choice of reducing agent, temperature, and pH conditions, enabling formation of alloyed or phase-separated structures depending on synthesis parameters. Protective agents and surfactants play crucial roles in controlling particle size, shape, and aggregation during wet chemical synthesis.

High-temperature synthesis methods enable the formation of thermodynamically stable intermetallic compounds and well-defined bimetallic phases that are difficult or impossible to achieve through room-temperature approaches. Thermal annealing of co-deposited or mechanically mixed metal precursors at elevated temperatures promotes atomic interdiffusion and phase transformation, converting metastable structures into equilibrium phases [8]. For copper-zinc systems, annealing at temperatures between three hundred and five hundred degrees Celsius induces brass phase formation with ordered atomic arrangements that exhibit superior catalytic properties and stability compared to disordered solid solutions. The annealing atmosphere significantly influences the final catalyst properties, with reducing atmospheres such as hydrogen or forming gas preventing oxidation while enabling structural rearrangement.

4.3. Support Materials and Interface Engineering

The support material constitutes an integral component of dual-metal catalyst systems, influencing not only the dispersion and stability of metal active sites but also participating in the catalytic process through electronic interactions and reactant adsorption. Carbon-based supports including activated carbon, carbon nanotubes, and graphene offer high surface areas, excellent electrical conductivity, and chemical stability under electrochemical conditions [10]. The surface chemistry of carbon supports can be modified through heteroatom doping with nitrogen, sulfur, phosphorus, or boron, creating coordination sites that anchor metal nanoparticles and tune their electronic properties.

Metal oxide supports such as titanium dioxide, cerium oxide, and zinc oxide provide alternative platforms with distinct properties including defined crystal facets, oxygen vacancy defects, and metal-support interaction effects [1]. The reducibility of oxide supports influences their behavior under electrochemical reducing conditions, with some oxides remaining stable while others undergo partial reduction that modifies their properties. Strong metal-support interactions can stabilize small metal clusters and single atoms through electronic coupling and geometric confinement effects. Interface engineering between metal active sites and support materials represents a critical aspect of catalyst design that profoundly influences catalytic performance [12].

5. Performance Optimization and Future Directions

5.1. Activity and Selectivity Enhancement

Comprehensive evaluation of dual-metal catalysts for electrochemical carbon dioxide reduction requires assessment of multiple performance metrics including activity, selectivity, stability, and energy efficiency. Activity is typically quantified through current density measurements at a given potential, with higher current densities indicating faster reaction kinetics and greater catalytic effectiveness [5]. However, current density alone provides incomplete information, as competing reactions such as hydrogen evolution also contribute to the total current. Faradaic efficiency, which represents the fraction of charge consumed for a specific product, serves as the primary selectivity metric. High-performance catalysts achieve faradaic efficiencies exceeding sixty percent for desired products while maintaining current densities above one hundred milliamperes per square centimeter at reasonable overpotentials.

The optimization of dual-metal catalysts involves systematic variation of composition, structure, and synthesis conditions to identify optimal configurations for specific target products [14]. Computational screening using density functional theory enables rapid evaluation of numerous metal combinations and structural motifs, identifying promising candidates before experimental synthesis [13]. Machine learning approaches further accelerate catalyst discovery by recognizing patterns in structure-property relationships and predicting optimal compositions. The integration of high-throughput synthesis and automated testing platforms enables experimental validation of computational predictions at unprecedented speeds.

5.2. Stability and Practical Implementation

Stability assessment involves monitoring catalyst performance over extended operation periods, typically ranging from tens to hundreds of hours for research-scale studies. Performance degradation can result from various mechanisms including metal dissolution, particle aggregation, surface oxidation, or poisoning by impurities [10]. Accelerated stability testing protocols employing potential cycling or elevated current densities enable prediction of long-term behavior within shorter experimental timeframes. Energy efficiency, quantified through the cathodic energy efficiency metric that accounts for both the thermodynamic potential and overpotential, determines the practical viability of catalytic processes.

Despite significant progress in dual-metal catalyst development, several fundamental challenges remain that require continued research efforts. The stability of bimetallic catalysts under electrochemical operating conditions represents a persistent concern, as potential cycling, high current densities, and reactive intermediates can induce structural changes including phase separation, metal dissolution, and surface reconstruction [1]. Understanding the mechanisms of catalyst degradation and developing strategies to enhance stability constitute critical priorities for practical implementation. Protective coating strategies, ligand stabilization approaches, and alloying with corrosion-resistant metals offer potential pathways to improve catalyst durability.

5.3. Scale-Up and Industrial Perspectives

Scaling up laboratory-scale findings to industrially relevant conditions poses substantial technical and economic challenges that extend beyond catalyst optimization alone. Industrial carbon dioxide reduction processes require high current densities exceeding three hundred milliamperes per square centimeter to achieve economically viable production rates, significantly exceeding typical laboratory test conditions [5]. Operating at such high current densities introduces mass transport limitations, increased local pH gradients, and elevated temperatures that affect catalyst behavior and product selectivity. Reactor engineering considerations including electrode design, electrolyte composition, and product separation systems become equally important as catalyst performance in determining overall process efficiency.

Future opportunities in dual-metal catalyst research encompass both fundamental scientific inquiries and applied technology development directions. The rational design of catalysts with atomic precision using computational screening and machine learning approaches promises to accelerate discovery of optimal metal combinations and structures [13]. High-throughput experimental methods coupled with automated characterization and testing enable rapid exploration of composition and structure spaces. The development of operando characterization techniques provides real-time insights into active site structure and reaction mechanisms under working conditions. Understanding structure-performance relationships at the atomic level will guide the design of next-generation catalysts with unprecedented activity, selectivity, and stability for sustainable carbon dioxide conversion.

6. Conclusion

Dual-metal catalysts represent a transformative approach for electrochemical carbon dioxide conversion, offering synergistic effects that overcome limitations of single-metal systems. The strategic combination of two metals enables optimization of electronic structures, geometric arrangements, and catalytic mechanisms to enhance activity, selectivity, and stability. Copper-based bimetallic catalysts, particularly copper-palladium, copper-bismuth, and copper-zinc systems, demonstrate remarkable performance improvements through complementary metal functions and cooperative catalytic pathways. Electronic and geometric effects in these systems modify intermediate binding energies, facilitate carbon-carbon coupling, and suppress competing hydrogen evolution. Advanced synthetic strategies including electrochemical deposition, chemical reduction, and thermal treatment enable precise control over catalyst composition and structure. Support materials and interface engineering further enhance catalytic properties through electronic interactions and geometric confinement effects. While significant progress has been achieved, challenges remain in achieving industrial-scale implementation including catalyst stability, energy efficiency, and economic viability. Future research directions emphasizing computational catalyst design, operando characterization, and scale-up engineering promise to advance dual-metal catalysts toward practical applications in sustainable carbon dioxide utilization. The continued development of these catalytic systems holds tremendous potential for addressing climate change challenges while enabling production of valuable chemicals and fuels from carbon dioxide feedstocks.

References

1. H. Wang and L. Yan, "Recent Advances in Single-Atom Catalysts for High-Performance Carbon Dioxide Electroreduction: Synthetic Strategies and Electrochemical Frontiers," *International Journal of Electrochemical Science*, p. 101131, 2025, doi: 10.1016/j.ijoes.2025.101131.
2. M. Li, H. Wang, W. Luo, P. C. Sherrell, J. Chen, and J. Yang, "Heterogeneous Single-Atom Catalysts for Electrochemical CO2 Reduction Reaction," *Advanced Materials*, vol. 32, no. 34, p. 2001848, 2020, doi: 10.1002/adma.202001848.
3. F. Ding, C. Ma, W.-L. Duan, and J. Luan, "Second auxiliary ligand induced two coppor-based coordination polymers and urease inhibition activity," *Journal of Solid State Chemistry*, vol. 331, pp. 124537–124537, 2023, doi: 10.1016/j.jssc.2023.124537.
4. F. Zhou, J. Zhang, Y. Zhang, Y. Wu, Y. Wang, and W. Luo, "Palladium-Copper bimetallic catalysts for electroreduction of CO2 and nitrogenous species," *Coordination Chemistry Reviews*, vol. 509, p. 215802, 2024, doi: 10.1016/j.ccr.2024.215802.
5. J. Feng, Y. Wang, G. Li, Q. Xue, M. Wang, and X. Sun et al., "CO2 electroreduction to C2+ products with ampere-level current density over sodium citrate modified Cu2O," *Applied Catalysis B: Environment and Energy*, vol. 366, p. 125014, 2025, doi: 10.1016/j.apcatb.2024.125014.
6. L. Li, X. Jin, X. Yu, and M. Zhong, "Bimetallic Cu-Bi catalysts for efficient electroreduction of CO2 to formate," *Frontiers in Chemistry*, vol. 10, 2022, doi: 10.3389/fchem.2022.983778.
7. T. Deng, S. Jia, S. Han, J. Zhai, J. Jiao, and X. Chen et al., "Electrochemical CO2 reduction to C2+ products over Cu/Zn intermetallic catalysts synthesized by electrodeposition," *Frontiers in Energy*, vol. 18, no. 1, pp. 80–88, 2024, doi: 10.1007/s11708-023-0898-0.

8. L. Wan, X. Zhang, J. Cheng, R. Chen, L. Wu, and J. Shi et al., "Bimetallic Cu–Zn Catalysts for Electrochemical CO2 Reduction: Phase-Separated versus Core–Shell Distribution," *ACS Catalysis*, vol. 12, no. 5, pp. 2741–2748, 2022, doi: 10.1021/acscatal.1c05272.
9. F. Ding, N. Su, C. Ma, B. Li, W.-L. Duan, and J. Luan, "Fabrication of two novel two-dimensional copper-based coordination polymers regulated by the 'V'-shaped second auxiliary ligands as high-efficiency urease inhibitors," *Inorganic Chemistry Communications*, vol. 170, p. 113319, 2024, doi: 10.1016/j.inoche.2024.113319.
10. C. Wang, H. Lai, H. Warkentin, C.-T. Dinh, and Q. Zhang, "Catalysts for electrochemical CO2 conversion: material sustainability perspective," *npj Materials Sustainability*, vol. 3, no. 1, pp.1-11, 2025, doi: 10.1038/s44296-025-00065-9.
11. X. Chen, J. Hu, J. Liu, P. Hai, and J. Guan, "Advances in dual-atom catalysts for the electroreduction of carbon dioxide," *Chemical Engineering Journal*, vol. 522, p. 167504, 2025, doi: 10.1016/j.cej.2025.167504.
12. G. Xie, W. Guo, Z. Fang, Z. Duan, X. Lang, D. Liu, G. Mei, Y. Zhai, X. Sun, and X. Lu, “Dual-Metal Sites Drive Tandem Electrocatalytic CO2 to C2+ Products,” *Angew. Chem.*, vol. 136, no. 47, p. e202412568, 2024, doi: 10.1002/ange.202412568.
13. Z. Bai, Z. Zhi, X. Z. Jiang, and K. H. Luo, "Rational Design of Dual-Atom Catalysts for Electrochemical CO2 Reduction to C1 and C2 Products with High Activity and Selectivity: A Density Functional Theory Study," *Industrial & Engineering Chemistry Research*, vol. 64, no. 8, pp. 4378–4387, 2025, doi: 10.1021/acs.iecr.4c04831.
14. X. Wang, Q. Chen, Y. Zhou, H. Li, J. Fu, and M. Liu, "Cu-based bimetallic catalysts for CO2 reduction reaction," *Advanced Sensor and Energy Materials*, vol. 1, no. 3, p. 100023, 2022, doi: 10.1016/j.asems.2022.100023.
15. Mulatu Kassie Birhanu, M.-C. Tsai, A. Kahsay, C.-T. Chen, Tamene Simachew Zeleke, and Kassa Belay Ibrahim et al., "Copper and Copper-Based Bimetallic Catalysts for Carbon Dioxide Electroreduction," *Advanced Materials Interfaces*, vol. 5, no. 24, p. 1800919, 2018, doi: 10.1002/admi.201800919.