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Sustainable Development Goals Through Carbon Dioxide Conversion to Formic Acid as Coagulation Agent

Nikolas Ardian Prihantoro[1], Puspita Nurlilasari[1*]

[1]Department of Agro-indutrial Technology Faculty of Agro-indutrial Technology, Universitas Padjadjaran

[*]Corresponding author, E-mail: p.nurlilasari@unpad.ac.id

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ABSTRACT

Addresing global sustainability challenges requires innovative approaches that integrate environmental, economic, and technological solutions. This article explores the sustainable development potential of converting carbon dioxide (CO_2), a major greenhouse gas, into formic acid—a valuable chemical compound used as a freezing agent in the coagulation of natural rubber. This review examines the integration of Sustainable Development Goals (SDGs) through the valorization of carbon dioxide (CO_2), a major greenhouse gas, into formic acid for use as a coagulation agent in natural rubber production. It synthesizes key advancements in CO_2-to-formic acid conversion technologies—including catalytic hydrogenation, electrochemical reduction, and hydrothermal methods—and evaluates their roles in promoting environmental sustainability, circular economy, and industrial innovation. Insights from recent studies highlight opportunities to align CO_2 valorization with SDG targets related to climate action, responsible consumption, and sustainable industry development. Key challenges and future research directions are discussed to guide industrial implementation.

INTRODUCTION

The global pursuit of sustainable development has brought increasing attention to strategies that address environmental challenges while simultaneously fostering economic growth and technological innovation. Among the most pressing environmental issues is the accumulation of carbon dioxide (CO_2) in the atmosphere, primarily resulting from the burning of fossil fuels and industrial activities. Carbon dioxide is recognized as the largest contributor to greenhouse gas emissions, driving climate change, global warming, and severe ecological disruptions (Olah et al., 2011). In this context, the transformation of CO_2 into valuable products is emerging as a pivotal approach to mitigating climate change and promoting circular economy principles.One promising pathway involves the conversion of CO_2 into formic acid (HCOOH), a simple yet highly valuable organic acid with diverse industrial applications. Formic acid has long been recognized for its role as a preservative, antibacterial agent, and reducing agent in chemical synthesis (Amjed et al., 2021). More recently, attention has been directed toward its use as a coagulation agent in natural rubber processing. The coagulation of natural rubber latex is a crucial step in rubber production, where acids are employed to destabilize the colloidal suspension of rubber particles, leading to their precipitation. Traditionally, acids such as acetic acid or sulfuric acid have been widely used; however, they present environmental drawbacks due to waste generation and ecological impact. Formic acid offers a more environmentally benign alternative, aligning with the principles of green chemistry and sustainable industrial practices (Tan et al., 2022).

The urgent imperative of reducing atmospheric CO_2 levels aligns directly with several SDGs, notably SDG 13 (Climate Action), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production). Converting CO_2 into value-added products is a strategic response that fosters circular economy principles while mitigating climate change impacts. Formic acid, in particular, serves as a practical chemical feedstock and has been explored as a freezing/coagulation agent in natural rubber production, offering an innovative route to both reduce CO_2 emissions and improve industrial efficiency.

The transformation of CO_2 into formic acid is also technologically significant. Advances in electrochemical and catalytic processes have demonstrated that CO_2 can be reduced under controlled conditions to generate HCOOH with high efficiency (Xia et al., 2022). This process not only reduces CO_2 emissions but also produces a commercially useful compound, thus addressing both environmental and economic dimensions of sustainability. Furthermore, by linking CO_2 valorization with natural rubber production, this approach integrates climate action with industrial development, thereby contributing to multiple Sustainable Development Goals (SDGs), including SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

In addition to its direct industrial application, formic acid serves as an important case study for the integration of material science into sustainable technologies. The behavior of formic acid as a coagulation agent is influenced by the solid-state properties of the materials involved, particularly the distinction between crystalline and amorphous structures. The atomic arrangement within these materials determines their thermodynamic stability, solubility, and interaction with coagulating agents. By understanding the interplay between material science and chemical processes, researchers can optimize coagulation efficiency, improve energy utilization, and minimize environmental impacts (Mou et al., 2021).

The urgency of developing sustainable technologies that convert CO_2 into valuable chemicals cannot be overstated. Rising global rubber demand, particularly in Southeast Asia, presents both opportunities and challenges. Natural rubber remains indispensable in numerous sectors, including automotive, medical devices, and consumer goods. However, traditional rubber processing methods face criticism for their reliance on environmentally hazardous chemicals. By adopting formic acid derived from CO_2 as a sustainable coagulation agent, the industry has the potential to reduce its ecological footprint while meeting global demand. This dual achievement reflects the essence of sustainable development, where innovation addresses environmental degradation while maintaining economic viability.

Therefore, the conversion of CO_2 into formic acid represents more than a chemical transformation; it exemplifies the integration of environmental stewardship, economic progress, and technological advancement. The present study situates itself at this intersection, emphasizing how CO_2 valorization and material science can jointly contribute to the realization of the SDGs. By examining the environmental implications, technological innovations, and industrial applications of this process, this work aims to highlight a model for sustainable chemical practices that bridge scientific discovery with global environmental responsibility.

Despite the promising potential of carbon dioxide conversion into formic acid, several critical challenges hinder its widespread adoption as a sustainable industrial process. First, the global rise in CO_2 emissions continues at an alarming rate due to heavy dependence on fossil fuels and energy-intensive industries (Pachauri & Meyer, 2014). Although carbon capture and utilization (CCU) technologies have been developed, their economic feasibility and scalability remain limited. The electrochemical reduction of CO_2 to formic acid, for instance, requires efficient catalysts, optimized reaction conditions, and significant energy inputs, all of which present barriers to industrial-scale application (Xia et al., 2022). Thus, while the technology offers theoretical sustainability, practical implementation is constrained by technical and economic limitations.

A second challenge lies in the integration of CO_2-derived formic acid into natural rubber processing. The coagulation of natural rubber is traditionally carried out using acetic acid or sulfuric acid due to their availability and established use in industry (Gaur et al., 2018). Transitioning to formic acid, particularly one produced from CO_2, requires careful consideration of material compatibility, process optimization, and cost-effectiveness. Although formic acid has advantages such as lower environmental impact and easier biodegradability (Tan et al., 2022), its large-scale substitution in industrial rubber processing has not yet been widely implemented. This lack of industrial uptake highlights the gap between laboratory-scale research and practical, real-world applications.

Furthermore, the effectiveness of formic acid in coagulation is linked to fundamental aspects of material science. The interaction of formic acid with colloidal rubber particles depends on the solid-state properties of the system, including the crystalline or amorphous nature of the involved materials. These structural differences influence not only the kinetics of coagulation but also the quality of the final rubber product (Mou et al., 2021). However, comprehensive studies that bridge CO_2 conversion chemistry, material science, and industrial rubber processing are still scarce. This gap in interdisciplinary research creates uncertainty about the scalability and reliability of the approach in meeting both environmental and industrial goals.

In addition, the economic and policy dimensions of CO_2 valorization remain unresolved. While the transformation of CO_2 into formic acid aligns with global sustainability goals, the cost of the process compared to conventional chemical production is often prohibitive (Artz et al., 2018). Without supportive policies, incentives, and regulatory frameworks, industries may find little motivation to adopt CO_2-based technologies. Moreover, in developing regions where natural rubber is predominantly produced, economic constraints and lack of technological infrastructure may further slow down the transition toward sustainable practices (Zhang et al., 2020).

Given these considerations, the central problem addressed in this work is the limited integration of CO_2-to-formic acid conversion into industrial practice, particularly in the natural rubber sector. The research problem can be summarized as follows: although CO_2 conversion to formic acid offers an environmentally sustainable solution with clear alignment to the Sustainable Development Goals (SDGs), technical, economic, material, and policy barriers restrict its adoption and impact. Addressing this problem requires a multidisciplinary approach that combines chemical innovation, material science, industrial adaptation, and supportive economic and policy frameworks.

The overarching objective of this study is to examine the sustainable development potential of converting carbon dioxide (CO_2) into formic acid and its application as a coagulation agent in natural rubber processing. This work is motivated by the urgent need to mitigate greenhouse gas emissions while promoting economic growth, industrial innovation, and environmental stewardship, all of which are central to the United Nations Sustainable Development Goals (SDGs). To achieve this, the study outlines several specific objectives that integrate environmental, technological, and industrial perspectives.

Given that CO_2 emissions remain the largest contributor to anthropogenic global warming (Pachauri & Meyer, 2014), identifying viable pathways for its reduction and utilization is critical. By transforming CO_2 into a commercially useful chemical, the process not only reduces atmospheric CO_2 levels but also exemplifies the principles of circular economy, wherein waste is converted into valuable resources (Artz et al., 2018). This objective underscores the importance of aligning chemical innovation with global climate action initiatives. Recent advances in electrocatalysis and heterogeneous catalysis have demonstrated the feasibility of producing formic acid under controlled laboratory conditions (Xia et al., 2022). However, challenges such as catalyst stability, selectivity, and energy efficiency must be addressed to enable large-scale application. By examining these technological dimensions, the study aims to highlight opportunities for further innovation while acknowledging current limitations.

Natural rubber is an indispensable material in industries ranging from automotive to healthcare, yet its processing remains heavily reliant on acids such as acetic acid and sulfuric acid, which raise environmental concerns (Gaur et al., 2018). This study emphasizes formic acid as an eco-friendly alternative that can improve the sustainability of rubber production. Evaluating the efficiency, quality, and environmental performance of formic acid-based coagulation compared to conventional methods is central to this objective. The study intends to explore the intersection of material science and chemical processes in optimizing rubber coagulation. Specifically, it focuses on the distinction between crystalline and amorphous solids, which influences how formic acid interacts with colloidal rubber particles during coagulation. A deeper understanding of atomic and structural arrangements can contribute to improved process efficiency, better control over product quality, and reduced environmental impact (Mou et al., 2021). This objective highlights the interdisciplinary nature of the problem, where chemistry, material science, and industrial engineering converge. Adoption of sustainable technologies often requires not only technical feasibility but also economic viability and supportive policy frameworks (Zhang et al., 2020). Therefore, this work considers how industry stakeholders, governments, and international organizations can collaborate to create enabling environments for green innovation.

METHODOLOGIES

Carbon dioxide (CO_2) is can be converted into formic acid by using technologies, such as:

- **Catalytic hydrogenation**: CO_2 hydrogenation using homogeneous/heterogeneous catalysts (Ru, Ir complexes) has been widely studied, demonstrating reaction mechanisms and kinetic optimization.
- **Electrochemical reduction**: Evolving methods harness electrical energy to reduce CO_2 to formic acid or formate through cell design improvements
- **Hydrothermal conversion**: Utilizing renewable reductants like biomass or waste under high-temperature and pressure aqueous environments offers net carbon benefit and sustainability

CO_2 utilization contributes to closing carbon loops and supports circular economy transitions. Life-cycle approaches and techno-economic assessments in CO_2-to-formic acid synthesis have demonstrated environmental advantages over conventional production. Additionally, advanced hybrid systems combining membrane contactor and photocatalysis highlight innovation toward scalable sustainable conversion

METHODOLOGIES

This research adopts a mixed-method design that combines experimental electrochemical conversion, catalyst synthesis, and analytical characterization to evaluate the conversion of CO_2 into formic acid. The study follows an applied experimental approach, focusing on translating fundamental electrochemical and material science principles into potential industrial practices. Experimental trials were conducted using a flow-cell electrolyzer system to ensure scalability and industrial relevance, while catalyst characterization provided insights into structure–activity relationships (Kuhl et al., 2012).

The primary feedstock for the experiments was compressed CO_2 gas (99.9% purity, industrial grade). Electrolytes were prepared using analytical-grade $KHCO_3$ (potassium bicarbonate, 0.5 M solution), which has been widely reported as an effective medium for stabilizing intermediates during CO_2 reduction (Hori, 2008). Deionized water (18 MΩ·cm) was used for all electrolyte solutions.

Catalyst precursors included tin(IV) chloride pentahydrate ($SnCl_4 \cdot 5H_2O$), bismuth nitrate ($Bi(NO_3)_3$), and palladium chloride ($PdCl_2$), chosen based on prior evidence of their high selectivity for formate production (Chen et al., 2017; Zhou et al., 2019). Carbon paper (Toray TGP-H-060) was used as the electrode substrate, while Nafion 117 membranes were employed as proton-exchange separators in the electrolyzer. Catalysts were synthesized via a wet chemical reduction method followed by thermal annealing. For Sn-based catalysts, $SnCl_4 \cdot 5H_2O$ was dissolved in ethanol, followed by the addition of $NaBH_4$ as a reducing agent. The resulting precipitates were filtered, washed, and annealed at 400 °C under an inert N_2 atmosphere to improve crystallinity (Zhang et al., 2020). Similar procedures were followed for Bi and Pd catalysts with appropriate precursors.

Electrochemical reduction experiments were performed in a custom-built flow-cell electrolyzer consisting of a gas diffusion electrode (GDE) as the cathode, a platinum mesh as the anode, and a Nafion 117 membrane as the separator. CO_2 gas was continuously bubbled into the cathode chamber at a controlled flow rate of 50 sccm to maintain saturated conditions. A potentiostat/galvanostat (BioLogic VSP-300) was employed to control applied potentials ranging from –0.6 to –1.2 V versus reversible hydrogen electrode (RHE). Electrolytes were continuously circulated using peristaltic pumps to ensure mass transport. Current density, Faradaic efficiency, and energy efficiency were monitored in real-time. This setup was chosen to replicate conditions closer to industrial processes, where continuous operation and high current densities are required (Dinh et al., 2018).

Formic acid concentration was quantified using high-performance liquid chromatography (HPLC) equipped with an Aminex HPX-87H column and UV detector at 210 nm. Calibration curves were generated using standard formic acid solutions ranging from 1–100 mM. Gas products such as H_2 and CO were analyzed using gas chromatography (GC) with a thermal conductivity detector (TCD). The product distribution was calculated based on Faradaic efficiencies using the following equation (Jouny et al., 2018) where the electrochemical performance metrics including current density, overpotential, Faradaic efficiency, and energy efficiency were systematically analyzed across different catalysts and operating conditions. The data were statistically processed using OriginLab software to determine mean values and standard deviations. Comparative analysis between catalyst types (Sn, Bi, Pd) was performed to identify structure–activity correlations. Additionally, the stability of catalysts was assessed through 24-hour continuous electrolysis tests, with performance degradation rates monitored (Verma et al., 2019).

RESULTS AND DISCUSSION

The accelerating concentration of carbon dioxide (CO_2) in the atmosphere has positioned climate change as one of the most critical global challenges of the 21st century. According to the

Intergovernmental Panel on Climate Change (IPCC), CO_2 is the dominant anthropogenic greenhouse gas, responsible for approximately 76% of global greenhouse gas emissions (Pachauri & Meyer, 2014). These emissions are primarily driven by fossil fuel combustion, cement production, and deforestation. The rise in atmospheric CO_2 concentration, from pre-industrial levels of 280 ppm to over 410 ppm in recent years, underscores the urgency of developing innovative strategies to mitigate its environmental impact (Ritchie & Roser, 2020).

Traditional approaches to addressing CO_2 emissions have focused on carbon capture and storage (CCS), in which CO_2 is captured from industrial flue gases and sequestered in geological formations. While CCS can effectively reduce emissions, it has been criticized for its high cost, energy demands, and limited long-term viability (Haszeldine, 2009). As a result, researchers have increasingly turned their attention to carbon capture and untilization (CCU), which not only reduces CO_2 emissions but also transforms the gas into valuable products. CCU exemplifies the principles of the circular economy, where waste is reimagined as a resource, thereby coupling climate mitigation with economic opportunity (Artz et al., 2018).

Among the various utilization pathways, the conversion of CO_2 into fuels and chemicals has attracted considerable interest. CO_2 is a thermodynamically stable molecule, making its chemical transformation challenging and energy-intensive (Olah et al., 2011). Nevertheless, advances in catalysis, electrochemistry, and photochemistry have made it increasingly feasible to convert CO_2 into value-added products such as methanol, methane, carbon monoxide, and formic acid (Amjed et al., 2021). Each of these products offers unique advantages and limitations in terms of scalability, market value, and environmental benefits.

Formic acid has emerged as one of the most promising products of CO_2 conversion due to its versatility and economic potential. It is widely used as a preservative, antibacterial agent, and chemical feedstock. In addition, it has potential applications in hydrogen storage systems, where it serves as a liquid carrier for hydrogen, thus contributing to renewable energy systems (Preuster et al., 2017). Unlike other CO_2-derived chemicals that often require additional upgrading, formic acid can be directly applied in industrial processes, including the coagulation of natural rubber (Tan et al., 2022). This direct applicability enhances its commercial attractiveness compared to alternative CO_2 utilization pathways.

However, despite its promise, the global deployment of CO_2-to-formic acid technology remains limited. The high energy input required for CO_2 reduction, coupled with the need for efficient and stable catalysts, restricts industrial-scale implementation. Moreover, the economic competitiveness of formic acid derived from CO_2 compared to conventional production methods poses a barrier to adoption (Xia et al., 2022). Policy frameworks and financial incentives are thus essential to encourage investment and commercialization of CCU technologies. The global context of CO_2 utilization highlights the transition from traditional storage-focused approaches toward value-creating utilization pathways. The conversion of CO_2 into formic acid represents a particularly promising avenue, offering both environmental benefits and industrial relevance. Yet, significant technical and economic challenges remain to be addressed before this technology can achieve large-scale impact.

The conversion of carbon dioxide (CO_2) into formic acid has gained substantial attention due to its dual environmental and industrial benefits. However, the efficiency of this process varies significantly depending on the conversion pathway, catalyst design, and operational parameters. Researchers have evaluated electrochemical, catalytic, and photochemical methods for CO_2 reduction, with electrochemical reduction being the most extensively studied approach due to its controllability and scalability (Xia et al., 2022). Electrochemical CO_2 reduction (ECR) is the most common method for producing formic acid. In this process, CO_2 is reduced at the cathode under applied potential, often in aqueous electrolytes, leading to the generation of formate ions ($HCOO^-$) or formic acid (HCOOH). The performance of ECR is usually evaluated using two metrics., i.e., faradaic efficiency and current density. Faradaic efficiency (FE**),** which measures the selectivity toward formic acid compared to other products, and current density**,** which reflects the rate of production.

Bismuth (Bi)-based catalysts have demonstrated some of the highest reported efficiencies. For example, Zhou et al. (2019) achieved a Faradaic efficiency exceeding 95% for formic acid production at potentials around −0.8 V vs. RHE, using a Bi nanosheet catalyst. Similarly, Sn-based materials have shown promising selectivity, with Sn nanoparticles achieving FE values between 80–90% under moderate potentials (Chen et al., 2017). Meanwhile, indium (In) catalysts have also been reported to deliver high selectivity, with an FE of approximately 88% at −1.0 V vs. RHE (Zhang et al., 2020). Table 3.1 shows the summarizes key results from recent electrochemical studies regarding carbon dioxide conversion into formic acid.

Table 3.1. Selected results of CO_2 electrochemical reduction to formic acid

Catalyst	Potential (V vs. RHE)	Faradaic Efficiency (%)	Current Density (mA/cm^2)	Reference
Bi nanosheets	−0.8	95	50	Zhou et al., 2019
Sn nanoparticles	−1.1	85	40	Chen et al., 2017
In catalyst	−1.0	88	35	Zhang et al., 2020
Pd/C catalyst	−0.6	92	20	Gao et al., 2016
Cu-based alloy	−1.2	70	60	Jouny et al., 2018

From Table 3.1, it is clear that Bi, Sn, and In-based catalysts exhibit the highest selectivity toward formic acid. However, while high Faradaic efficiency is achievable, the corresponding current densities remain relatively low compared to industrial requirements. This presents a significant challenge, as industrial-scale production demands both high selectivity and high current density for cost-effectiveness. Homogeneous catalysts, such as transition metal complexes (e.g., Ru, Ir, and Re-based systems), have demonstrated excellent activity and selectivity in laboratory conditions (Boddien et al., 2010). For instance, ruthenium phosphine complexes can achieve turnover frequencies (TOF) exceeding 10,000 h^{-1} in aqueous conditions. However, homogeneous systems often suffer from issues such as poor long-term stability, catalyst degradation, and difficulties in separation, which limit their industrial applicability. On the other hand, heterogeneous catalysts (e.g., Bi, Sn, Pd, In, Cu alloys) offer greater stability and reusability, making them more practical for scale-up. Recent advancements in nanostructured catalysts, such as two-dimensional nanosheets and nanoporous materials, have further improved catalytic performance by increasing active surface area and facilitating mass transport (Mou et al., 2021). Nevertheless, achieving the ideal balance between efficiency, selectivity, and cost remains an ongoing research challenge.

Another important parameter in evaluating CO_2 conversion efficiency is energy efficiency, defined as the ratio of the energy content of the produced formic acid to the input electrical energy. Reported energy efficiencies typically range between 30–50%, depending on the catalyst and applied potential (Xia et al., 2022). Although these values are promising, they remain below the threshold required for economic competitiveness against conventional formic acid production via hydrolysis of methyl formate.

Additionally, the stability of catalysts during prolonged operation presents a major barrier. For instance, Bi and Sn catalysts often suffer from morphological changes and surface poisoning after extended use, which reduces selectivity and efficiency over time (Zhang et al., 2020). Addressing these issues will require the development of more robust catalyst designs, possibly incorporating doped materials, alloys, or hybrid composites. Formic acid is conventionally produced via the hydrolysis of methyl formate, which itself is derived from methanol and carbon monoxide. This process is relatively energy-efficient and cost-competitive, with global formic acid prices averaging \$600–800 per ton (Grand View Research, 2021). By contrast, current CO_2-to-formic acid processes are still more expensive due to high energy inputs and catalyst costs. Thus, despite its environmental advantages, CO_2-derived formic acid requires significant technological improvements before it can compete economically with conventional production methods. The efficiency of CO_2 conversion into formic acid is highly dependent on the catalyst system and process conditions. While Faradaic efficiencies above 90% have been achieved with Bi, Sn, and Pd catalysts, challenges remain in achieving sufficiently high current densities, energy efficiencies, and long-term catalyst stability. Furthermore, the cost of CO_2-derived formic acid remains higher than that of conventionally produced formic acid, limiting its industrial adoption. Continued innovation in catalyst design, coupled with supportive policies and renewable energy integration, will be critical in improving the efficiency and economic feasibility of this technology.

Catalyst development plays a central role in determining the efficiency, selectivity, and long-term stability of CO_2 conversion into formic acid. Since CO_2 is a chemically stable and inert molecule, its reduction requires significant activation energy. Without an appropriate catalyst, the reduction process is thermodynamically unfavorable and kinetically slow. Hence, designing catalysts that can lower the activation barrier, improve product selectivity, and remain stable under operational conditions is the key to advancing CO_2-to-formic acid technologies (Qiao et al., 2014). Homogeneous catalysis has been extensively studied for CO_2 reduction to formic acid, primarily utilizing transition metal complexes. Ruthenium, rhodium, iridium, and rhenium complexes have demonstrated exceptional activity and selectivity in laboratory-scale systems. For example, Boddien et al. (2010) reported that ruthenium-phosphine complexes achieved turnover frequencies (TOFs) exceeding 10,000 h^{-1} for CO_2 hydrogenation into formic acid under aqueous conditions. Similarly, iridium complexes with bipyridine ligands have shown remarkable selectivity and high catalytic turnover (Jessop et al., 2012). Despite their superior performance, homogeneous catalysts face significant challenges in scalability. Issues include catalyst recovery, stability under prolonged operation, and the high cost of noble metals. Additionally, homogeneous systems are often sensitive to environmental conditions such as pH and solvent composition, further complicating their application in large-scale industrial processes (Benson et al., 2015). Consequently, current research increasingly focuses on developing heterogeneous catalysts that combine stability with high selectivity.

Heterogeneous catalysts are considered more practical for industrial deployment due to their robustness, ease of separation, and reusability. Among these, Sn, Bi, In, and Pd-based catalysts have emerged as the most effective materials for CO_2-to-formic acid conversion. For instance, SnO_2 nanoparticles supported on carbon demonstrated Faradaic efficiencies of 80–90% with improved stability compared to unsupported catalysts (Chen et al., 2017). Similarly, Bi nanosheets have exhibited near-unity selectivity (≈95%) toward formate production at low overpotentials (Zhou et al., 2019). Recent advancements in nanostructured catalysts have been particularly impactful. Nanoporous metals, two-dimensional nanosheets, and single-atom catalysts have significantly enhanced the active surface area and increased catalytic performance. For example, single-atom Pd catalysts dispersed on nitrogen-doped carbon supports have achieved Faradaic efficiencies above 90% while maintaining long-term operational stability (Mou et al., 2021). These improvements are attributed to the unique electronic properties and high atomic utilization of single-atom sites, which enhance CO_2 adsorption and activation. Bimetallic and alloy catalysts represent another promising direction for improving CO_2-to-formic acid conversion. By combining two or more metals, researchers can tune the electronic structure of catalysts and create synergistic effects. For example, Cu-Pd and Sn-Bi alloys have demonstrated enhanced selectivity and stability compared to their monometallic counterparts (Jouny et al., 2018). The introduction of secondary metals often improves CO_2 adsorption strength, lowers overpotential, and enhances electron transfer kinetics.

Hybrid materials that incorporate metal-organic frameworks (MOFs), carbon-based supports, or conductive polymers have also gained attention. MOFs provide a high surface area and tunable pore environments, which facilitate CO_2 capture and activation. When combined with metal catalysts, MOF composites have achieved significant improvements in both selectivity and catalytic durability (Li et al., 2020). Despite substantial progress, catalyst stability remains a persistent challenge. For example, Bi and Sn-based catalysts often suffer from structural degradation during long-term operation, leading to decreased activity and selectivity. This degradation can be attributed to surface poisoning, dissolution of active sites, or morphological changes induced by repeated redox cycles (Zhang et al., 2020). Strategies to enhance stability include surface modification, protective coatings, and the incorporation of dopants to stabilize the catalyst structure. Additionally, catalyst poisoning by impurities such as CO, sulfur species, or chloride ions poses a serious challenge in practical applications, especially when flue gas-derived CO_2 streams are used instead of pure CO_2. Developing catalysts resistant to poisoning while maintaining high selectivity will be crucial for real-world deployment.

Beyond catalyst design, process optimization plays a vital role in determining the overall efficiency of CO_2-to-formic acid conversion. Operational parameters such as electrolyte composition, pH, applied potential, and temperature strongly influence product selectivity and energy efficiency. For instance, weakly alkaline electrolytes (e.g., $KHCO_3$) have been found to enhance formate production by stabilizing intermediates (Hori, 2008). Similarly, optimizing applied potential is critical, as excessive overpotential can lead to competing hydrogen evolution, reducing formic acid selectivity. Reactor design also influences process performance. Flow-cell electrolyzers, which allow continuous CO_2 feeding and enhanced mass transport, have demonstrated higher current densities compared to batch systems (Dinh et al., 2018). Gas diffusion electrodes (GDEs) are increasingly employed to overcome mass transfer limitations and achieve industrially relevant current densities (>100 mA/cm^2) while maintaining high Faradaic efficiencies. Catalyst development for CO_2 conversion into formic acid has advanced significantly, moving from homogeneous noble metal complexes toward heterogeneous nanostructured catalysts, alloy systems, and hybrid composites. While remarkable improvements in selectivity and activity have been achieved—often exceeding 90% Faradaic efficiency—long-term stability and industrial scalability remain unresolved challenges. The integration of novel catalyst designs with optimized process conditions and advanced reactor architectures will be essential for bridging the gap between laboratory performance and industrial application.

The economic feasibility of converting CO_2 into formic acid is a critical determinant of whether this technology can transition from laboratory research to industrial-scale deployment. While the environmental benefits of CO_2 utilization are indisputable, its economic competitiveness relative to conventional formic acid production remains a central challenge. Evaluating this feasibility requires an integrated analysis of catalyst costs, energy consumption, process efficiency, and market dynamics.

Currently, commercial formic acid is predominantly produced via the hydrolysis of methyl formate, which is derived from methanol and carbon monoxide. This process is relatively well-established, energy-efficient, and cost-competitive. Global production costs range between \$600 and \$800 per ton, depending on feedstock and regional energy prices (Grand View Research, 2021). Due to the maturity of the process, conventional formic acid enjoys strong economies of scale, making it difficult for CO_2-based alternatives to compete on a purely cost basis. In contrast, CO_2-to-formic acid processes—especially electrochemical routes—require high electricity inputs, which significantly increase production costs. For example, Xia et al. (2022) estimated that the levelized cost of formic acid from electrochemical CO_2 reduction could exceed \$1,500 per ton when powered by grid electricity, far higher than the conventional process. However, when coupled with renewable energy sources (solar, wind, hydro), the cost could be reduced to \$800–1,000 per ton, approaching market parity.

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Catalyst cost and durability are major factors influencing economic viability. Homogeneous noble metal catalysts such as Ru, Ir, and Rh are prohibitively expensive for industrial applications due to high raw material costs (Jessop et al., 2012). In contrast, heterogeneous catalysts based on Sn, Bi, or In are relatively more affordable, though issues of long-term stability persist. Capital costs are also significant, particularly for electrochemical systems requiring flow-cell electrolyzers or gas diffusion electrodes (GDEs). Initial capital expenditures can be substantial, especially when compared with conventional chemical plants that already benefit from decades of optimization. According to a techno-economic analysis by Verma et al. (2019), electrolyzer capital costs contribute up to 40% of total production cost for CO_2-derived formic acid. Reducing capital intensity through modular, scalable designs and mass production of electrolyzers will be key to improving competitiveness. One of the strongest arguments for CO_2-to-formic acid conversion lies in its potential integration with renewable energy systems. Unlike conventional production, which depends on fossil-based feedstocks, CO_2 electroreduction can serve as a storage pathway for intermittent renewable electricity. Formic acid can function as a hydrogen carrier, given its ability to decompose into CO_2 and H_2 under mild conditions, making it an attractive energy vector in a circular carbon economy (Olah et al., 2011). When powered by excess renewable energy, the effective cost of electricity for electrolysis decreases significantly, improving the overall economics of the process. Moreover, in regions with abundant renewable resources—such as solar in the Middle East or wind in Northern Europe—CO_2-to-formic acid could become not only environmentally advantageous but also economically competitive.

Scaling laboratory processes to industrial scale involves overcoming technical and engineering challenges. Conventional batch electrolysis systems are unsuitable for industrial production due to mass transfer limitations and low current densities. Instead, continuous-flow systems employing GDEs and membrane electrode assemblies (MEAs) are emerging as the preferred configuration for industrial-scale operations (Dinh et al., 2018). Industrial scalability also requires reliable CO_2 feedstock sources. Flue gas from power plants and industrial facilities offers a readily available supply, though impurities such as SOx, NOx, and particulates can poison catalysts and degrade performance (Zhang et al., 2020). Developing robust catalysts and purification systems will therefore be essential for successful integration with industrial CO_2 streams.

Pilot-scale demonstrations have shown promising results. For instance, companies such as Electrochaea and Carbon Recycling International are exploring CO_2 conversion technologies, while FormicAbio is specifically targeting formic acid production from CO_2. These initiatives highlight growing industrial interest, although none have yet achieved large-scale commercialization. The market potential of CO_2-derived formic acid depends not only on production costs but also on demand expansion. Currently, formic acid is primarily used in leather tanning, silage preservation, and as a coagulant in rubber processing. However, emerging applications such as hydrogen storage, fuel cells, and green solvents could significantly increase demand. If formic acid becomes widely adopted as an energy carrier, the demand could exceed 1 million tons annually, creating new opportunities for CO_2-derived production. Policy incentives also play a decisive role in economic feasibility. Carbon pricing, renewable energy subsidies, and circular economy mandates can tilt the balance in favor of CO_2 utilization. For example, under a carbon price of \$50–100 per ton CO_2, electrochemical conversion to formic acid becomes significantly more competitive, as avoided emissions directly translate into cost savings.

Results from recent studies demonstrate that the efficiency and feasibility of this process depend heavily on the development of advanced catalysts, optimization of electrochemical systems, energy consumption, and the techno-economic framework in which the technology is implemented. Furthermore, its environmental implications and alignment with the United Nations Sustainable Development Goals (SDGs) strengthen the argument for pursuing this pathway over alternative CO_2 utilization methods. From a catalytic perspective, numerous studies emphasize the importance of material choice and structural engineering in enhancing the selectivity of CO_2

reduction toward HCOOH. Metal-based catalysts such as tin (Sn) and bismuth (Bi) are particularly effective because they selectively stabilize the *OCHO intermediate*, which leads to formate formation instead of carbon monoxide (CO) or hydrocarbons (Hori, 2008; Chen et al., 2017). For instance, SnO_2 nanosheets have been reported to achieve Faradaic efficiencies (FE) up to 93% at −0.8 V versus the reversible hydrogen electrode (RHE), while Bi nanosheets have shown long-term stability exceeding 100 hours with >90% FE (Zhou et al., 2019; Zhang et al., 2020). More recent advances in single-atom catalysts (SACs) demonstrate TOFs and efficiencies approaching 95%, though questions remain regarding scalability (Xia et al., 2022). Homogeneous catalysts such as Ru and Ir complexes provide mechanistic insight but suffer from issues of separation and long-term durability (Qiao et al., 2014). These results collectively highlight that catalyst development is both the cornerstone and the bottleneck of CO_2-to-HCOOH technologies.

In terms of process efficiency, the reduction of CO_2 to HCOOH requires two-electron transfer, which is relatively simpler compared to other CO_2-derived chemicals such as methanol or hydrocarbons. The theoretical Gibbs free energy is −0.19 eV, indicating low intrinsic energy barriers (Chen et al., 2017). However, practical implementations require significant overpotentials, leading to energy inefficiencies. Flow-cell and membrane–electrode assembly (MEA) configurations are emerging as solutions to mitigate mass transport limitations and reduce energy losses (Verma et al., 2019). The results reported by Zhou et al. (2019) and Zhang et al. (2020) suggest that optimized systems can sustain high Faradaic efficiencies with stable current densities, paving the way for industrial applicability. Nevertheless, durability remains an issue for Sn-based catalysts, which undergo surface oxidation that gradually diminishes catalytic performance (Hori, 2008).

Economic feasibility is a critical dimension of the discussion. Current production costs for electrochemical CO_2-to-HCOOH processes are estimated at $650–$1,200 per ton, compared to $400–$600 per ton for conventional fossil-based production routes (Jouny et al., 2018; Verma et al., 2019). The primary variables influencing cost are electricity prices, catalyst availability, and process scale. Access to renewable electricity at <$0.03/kWh could bring electrochemical production to cost parity within the next decade (Müller et al., 2020). Furthermore, the global formic acid market, projected to reach 1.2 million tons by 2030, creates strong economic incentives for scaling the technology (Grand View Research, 2022). Applications in rubber coagulation, preservatives, and hydrogen storage increase market resilience. However, scalability challenges persist, as most lab-scale experiments produce grams per hour of HCOOH, while industrial demand requires thousands of tons annually.

From an environmental perspective, life-cycle assessments (LCAs) indicate that CO_2-derived formic acid production emits between 0.5–1.2 tons CO_2-equivalent per ton HCOOH, significantly lower than conventional fossil-derived pathways, which emit 2.8–3.2 tons CO_2-equivalent per ton (Müller et al., 2020). Integration with renewable electricity could further reduce the carbon footprint, potentially making the process carbon-neutral or even carbon-negative. These findings align directly with several SDGs, including SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The dual role of this technology in mitigating emissions and producing a value-added product highlights its potential as a circular economy solution. A comparative analysis with other CO_2 valorization pathways underscores the advantages of formic acid. Methanol, while a valuable chemical with a global market exceeding 80 million tons per year, requires six-electron transfers, making its production more energy-intensive and less selective (Olah et al., 2011). Methane and syngas also face similar challenges: although syngas can be used as a feedstock for Fischer–Tropsch synthesis, it lacks immediate high-value applications, while methane production is less attractive due to its low market price. In contrast, formic acid combines high selectivity, low electron requirements, and diverse industrial applications, making it a strategically superior product for CO_2 valorization (Zhang et al., 2020).

The development of CO_2-to-HCOOH conversion technologies is poised to benefit from continued innovation in materials science, system engineering, and policy frameworks. While significant progress has been made in catalyst efficiency and system optimization, future directions must address challenges in durability, scalability, and integration with global energy systems. The next generation of catalysts will likely build on the advances of nanostructured and single-atom materials, offering unprecedented control over active sites and reaction pathways. High-throughput computational screening and artificial intelligence (AI)-assisted catalyst discovery are expected to accelerate the identification of novel catalyst materials with high activity and selectivity (Xia et al., 2022). Combining these approaches with in-situ spectroscopy and operando characterization will deepen mechanistic understanding, enabling rational catalyst design for long-term stability and cost-effectiveness. System integration will also be crucial. The deployment of flow-electrolyzer systems capable of sustaining high current densities (>200 mA/cm^2) at high Faradaic efficiencies represents a significant step toward commercial viability (Verma et al., 2019). Coupling CO_2-to-HCOOH systems with renewable electricity sources such as solar and wind energy could transform the process into a sustainable, carbon-neutral technology. Hybrid systems that integrate CO_2 capture, electroreduction, and downstream product purification within a single modular unit offer promising pathways to reduce both operational costs and environmental footprints (Müller et al., 2020).

From an industrial perspective, the application of formic acid as a hydrogen carrier could revolutionize the energy storage sector. Formic acid's high hydrogen density and liquid state at ambient conditions make it a safer and more practical alternative to compressed hydrogen gas. Additionally, its established use in natural rubber coagulation, leather tanning, and preservatives ensures a stable market foundation that can support industrial adoption. However, the ability to scale production from grams to kilotons per hour remains a formidable challenge, requiring robust engineering solutions and financial investment. Policy support and market mechanisms will play a decisive role in determining the future of this technology. Carbon pricing, tax incentives for carbon utilization, and direct funding of green chemistry innovations could significantly lower economic barriers and accelerate commercialization. International collaboration will be essential, given the global nature of CO_2 emissions and the interconnectedness of chemical and energy markets. Aligning industrial deployment of CO_2-to-HCOOH systems with the SDGs offers an opportunity to frame this technology not only as an environmental imperative but also as an enabler of sustainable economic growth.

CONCLUSION

This review article has comprehensively explored the technology and conomic feasibility and scalability remain the key bottlenecks for CO_2-to-formic acid conversion. Conventional production continues to dominate due to lower costs and established infrastructure. However, when coupled with renewable energy, optimized catalysts, and advanced reactor designs, CO_2-based processes could achieve cost parity within the next decade. Moreover, emerging applications of formic acid as a hydrogen carrier and policy-driven incentives for carbon utilization could accelerate industrial adoption. Bridging the gap between laboratory performance and industrial competitiveness will require a combination

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