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Bioelectrochemical Enhancements for Scalable CO_2 Conversion in Biofuel Synthesis

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ABSTRACT

This study aims to explore bioelectrochemical enhancement for scalable CO_2 conversion in biofuel synthesis, with specific attention to the readiness, barriers, and implementation prospects of microbial electrosynthesis in Indonesia. The study used a qualitative exploratory case study design conducted from December 2025 to February 2026 in Bandung, South Tangerang, Cilegon, and Karawang. Data were collected through semi-structured interviews, limited observation, and document analysis involving 18 to 25 key informants, including bioelectrochemical researchers, microbiology experts, reactor technicians, biofuel practitioners, industrial emission managers, and energy or environmental policy actors. Thematic analysis identified four main findings: microbial electrosynthesis is considered promising but not yet production-ready; electrode performance and cathodic biofilm stability remain central technical bottlenecks; scale-up depends on reactor design, gas-liquid transfer, and continuous operation; and industrial implementation requires institutional, economic, and policy readiness. These findings show that scalable CO_2 conversion should not be understood only as a laboratory or reactor efficiency issue, but as a socio-technical process that requires alignment among technology, industry, policy, and infrastructure. The study contributes to the literature by positioning bioelectrochemical CO_2 conversion as an emerging pathway for low-carbon biofuel development and carbon valorization. Further research should integrate qualitative findings with techno-economic analysis and life-cycle assessment to strengthen evidence for industrial adoption.

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1. Introduction

The increase in CO_2 emissions and the need for low-carbon energy have encouraged the development of carbon conversion technologies that can transform waste gases into valuable products. One promising technology is microbial electrosynthesis, or MES, which uses electroactive microorganisms, electrodes, and electrical current to reduce CO_2 into organic compounds. Dessì et al. (2021) explain that MES can support sustainable biorefineries because it connects carbon emission reduction with the production of green chemicals. In biofuel synthesis, MES is relevant because it can produce acetate, methane, volatile fatty acids, and other intermediates that can be further converted into biofuel. Mirea et al. (2025) argue that the future of MES for next-generation biofuel production depends on electrode development, microbial community stability, reactor design, and integration with renewable energy systems.

This issue is important in Indonesia because national biofuel development still depends strongly on land-based feedstocks. Pambudi et al. (2023) show that Indonesia has large renewable energy potential, but its development still faces technological, infrastructural, regulatory, and investment barriers. In the biofuel sector, Halimatussadiah et al. (2021) explain that Indonesia's biodiesel policy supports energy security, but it can also create economic and environmental risks if increased feedstock demand leads to land expansion. Halimatussadiah et al. (2025) add that oil palm replanting schemes may support regional economies, but they still require strong technical and financial support. These conditions show the need for alternative biofuel pathways that do not rely only on biomass expansion. CO_2-based biofuel synthesis through bioelectrochemical systems can become one potential pathway because it connects carbon utilization, circular economy, and low-carbon energy transition.

Technically, MES works through electron transfer from the cathode to microorganisms that use CO_2 as a carbon source to form organic products. Mohanakrishna et al. (2020) show that homoacetogenic biocathodes can operate under high bicarbonate concentrations, although their performance depends on electrochemical conditions and microbial community stability. Roy et al. (2021) demonstrate that industrial CO_2 with low impurity levels can be directly used for acetate production through MES. These findings indicate that MES should not be understood only as a laboratory-based innovation. It must also be examined as a technological process that interacts with industrial gas characteristics, reactor stability, product selectivity, and long-term operational needs.

Electrodes and cathodic biofilms play central roles in improving bioelectrochemical performance. Flexer and Jourdin (2020) show that purposely designed porous electrodes can increase acetate production rates from CO_2 by expanding active surface area and improving microbe-electrode contact. Vassilev et al. (2022) state that cathodic biofilms are essential for MES because they influence electron transfer, microbial colonization, and process stability. Song et al. (2022) explain that biofilm matrix development and artificial mediators can improve electron transport in CO_2-based MES. Ibrahim et al. (2023) also emphasize that cathode development remains a key issue because it affects product selectivity, material cost, conversion efficiency, and technological sustainability. Therefore, bioelectrochemical enhancement needs to be viewed as an integrated process involving material science, microbiology, electrochemistry, and reactor engineering.

Scalability remains a major challenge in MES development. Rojas et al. (2021) found that adjusting CO_2 flow rate can improve gas-liquid mass transfer and influence acetate formation. Rovira-Alsina et al. (2020) show that thermophilic operation can support bioelectrochemical CO_2 recycling into organic compounds, especially when CO_2 comes from high-temperature industrial processes. Izadi et al. (2021) demonstrate that continuous operation can improve pH control, medium supply, and production efficiency. These studies show that MES scalability depends on reactor configurations that can maintain biological, electrochemical, and operational stability at the same time. This challenge becomes more complex when the system is expected to operate with industrial CO_2 sources and renewable electricity.

Recent studies also show that reactor innovation and electron mediation strategies may accelerate MES development toward applied biofuel systems. Bian et al. (2024) report that H_2-mediated mixed culture MES can increase acetate production from CO_2. Dessì et al. (2023) developed a three-chamber MES cell with a gas diffusion biocathode to improve acetate production under moderate saline conditions. Pan et al. (2024) introduced an electrolytic gas lift reactor to improve acetate production efficiency from CO_2. Cabau-Peinado et al. (2024) show that a directed flow-through MES reactor can reach productivity levels close to syngas fermentation and chain elongation fermentation. Bolognesi et al. (2022) further demonstrate that acetate from bioelectrochemical systems can be linked with microalgae-based bio-oil production. These findings indicate that MES has strong potential for integration into biofuel value chains, but its implementation still requires deeper understanding of technical readiness, institutional support, industrial acceptance, and economic feasibility.

Previous studies remain dominated by experimental and technical reviews that focus on reactor performance, Coulombic efficiency, microbial composition, electrode configuration, and product yield. Hengsbach et al. (2022) show that the use of pure or mixed cultures affects methane and acetate production in MES. Das et al. (2025) argue that green strategies, microbial engineering, and reactor development can strengthen the connection between MES and circular economy, but scalability remains unresolved. Jourdin and Burdyny (2021) also emphasize that MES must move beyond laboratory promise toward real technological application. Therefore, this study aims to explore how bioelectrochemical enhancements are understood as a strategy for scalable CO_2 conversion in biofuel synthesis. The study focuses on actors' experiences, perceptions, and evaluations of technological readiness, scale-up barriers, electrode and biofilm roles, industrial CO_2 integration, and implementation opportunities in Indonesia's energy transition. Theoretically, this study contributes to the understanding of MES as a socio-technical system. Practically, it can support researchers, industry actors, and policymakers in designing more realistic strategies for low-carbon biofuel development.

2. Materials and Methods

This study used a qualitative approach with an exploratory case study design. This approach was selected because the study aimed to understand the experiences, perceptions, and evaluations of actors involved in bioelectrochemical enhancement for scalable CO_2 conversion in biofuel synthesis. Lim (2025) explains that qualitative research is suitable when a study seeks to understand meaning, context, process, and human experience that cannot be fully explained through numerical measurement. The case study design was also relevant because MES is a complex technological phenomenon that involves electrode materials, microbial communities, reactor design, renewable electricity, industrial CO_2 sources, and energy transition policy. Since the study focused on technological readiness and implementation barriers, an exploratory case study provided an appropriate framework for examining both technical and non-technical dimensions in depth.

The study was conducted from December 2025 to February 2026 in Indonesia. The research sites were determined as Bandung, West Java; South Tangerang, Banten; Cilegon, Banten; and Karawang, West Java. Bandung was selected because it represents a higher education and laboratory-based research environment in bioenergy, environmental engineering, and electrochemical technology. South Tangerang was selected because it has national research institutions related to energy, environment, and applied technology. Cilegon was selected because it represents an industrial area with potential CO_2 emission sources from heavy industry. Karawang was selected because it represents an industrial and manufacturing area that is relevant to energy transition, waste gas management, and potential biofuel application. These locations were chosen to capture the relationship between laboratory innovation, research governance, industrial emission sources, and implementation opportunities.

The participants consisted of 18 to 25 key informants selected through purposive sampling. The informants included researchers in bioelectrochemical systems, microbiology or biofilm experts, reactor technicians, biofuel practitioners, industrial emission managers, and energy or environmental policy actors. The inclusion criteria were at least two years of experience in research, development, management, or evaluation related to MES, CO_2 conversion, biofuel, electrochemistry, bioprocess technology, or low-carbon energy policy. Campbell et al. (2020) explain that purposive sampling helps researchers select participants who have direct knowledge of the phenomenon being studied. Ahmad and Wilkins (2025) also emphasize that purposive sampling must be planned carefully so that participant selection aligns with the research objectives, research questions, and analytical strategy. Limited snowball sampling was used when initial informants recommended other actors with specific expertise in reactor development, industrial CO_2 utilization, or biofuel implementation.

Data were collected through semi-structured interviews, limited observation, and document analysis. Semi-structured interviews were used to explore informants' views on MES readiness, scale-up barriers, electrode design, cathodic biofilm stability, CO_2 mass transfer, microbial selection, energy requirements, operational costs, and industrial application prospects. Each interview lasted approximately 45 to 60 minutes and was recorded after obtaining participant consent. Limited observation was conducted in accessible laboratory spaces, reactor demonstration areas, technical discussions, or research activities related to bioelectrochemical systems. Document analysis included academic articles, research reports, energy policy documents, technical notes, and institutional documents related to biofuel, CO_2 conversion, and decarbonization. Cabau-Peinado et al. (2024) show that reactor innovation can improve MES productivity, while Bian et al. (2024) show that H_2 mediation can strengthen acetate production from CO_2. These findings guided the interview themes, especially questions related to reactor design, electron transfer pathways, and industrial scale-up.

Data validity was maintained through source triangulation, method triangulation, member checking, and audit trail. Source triangulation was conducted by comparing information from researchers, technicians, industry practitioners, and policy actors. Method triangulation was conducted by comparing interview data, observation notes, and documents. Ahmed (2024) explains that trustworthiness in qualitative research can be strengthened through credibility, transferability, dependability, and confirmability. Member checking was conducted by sending interview summaries or preliminary interpretations to selected informants to confirm meaning accuracy. An audit trail was maintained by storing interview guides, transcripts, observation notes, analytical memos, coding decisions, and theme revisions. This strategy helped ensure that the research process was transparent and could be traced by other researchers in similar contexts.

Data were analyzed using thematic analysis with both inductive and deductive patterns. The analysis included transcription, repeated reading, initial coding, code grouping, theme development, theme review, theme naming, and narrative interpretation. Ahmed et al. (2025) explain that thematic analysis helps researchers identify and interpret patterns of meaning in qualitative data systematically. Deductive categories were developed from the research focus, including technological readiness, scale-up barriers, electrode design, cathodic biofilm, energy efficiency, industrial CO_2 integration, and policy support. Inductive categories were developed from field data, especially when informants described issues such as limited access to electrode materials, lack of trained technicians, cost uncertainty, and low industrial confidence in long-term process stability. Naeem et al. (2024) explain that data saturation occurs when further data collection no longer produces significant new themes. Therefore, interviews were stopped when the main themes became repetitive and analytically stable.

The study followed ethical research principles. Each informant received information about the research objectives, form of participation, right to refuse certain questions, and confidentiality protection. Data related to patents, laboratory secrets, technical formulas, or sensitive industrial strategies were not reported directly. Names of individuals and institutions were anonymized when requested by participants or organizations. This study did not collect clinical data, patient data, or sensitive personal information. The methodological procedure was designed in detail to allow limited replication in similar bioelectrochemical technology contexts. Through this design, the study examined MES not only as a reactor efficiency issue, but also as a socio-technical process shaped by actors, institutions, infrastructure, policy, and low-carbon biofuel opportunities.

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3. Results and Discussions

The qualitative analysis generated four main findings: technological readiness, electrode and biofilm constraints, scale-up barriers, and socio-technical readiness for industrial implementation. These findings emerged from semi-structured interviews, limited observations, and document analysis conducted in Bandung, South Tangerang, Cilegon, and Karawang from December 2025 to February 2026. Overall, participants viewed bioelectrochemical CO_2 conversion as a promising low-carbon pathway for biofuel synthesis because it can connect carbon utilization, renewable electricity, and production of biofuel precursors. However, they also emphasized that the technology remains far from routine industrial use because its performance has not yet been proven under long-term and realistic operating conditions. The data show that participants did not assess MES only from the ability to produce acetate or other organic products. They also considered process stability, operational cost, reactor durability, human resource readiness, and industrial compatibility. This finding aligns with recent MES literature, which reports progress in reactor design and CO_2 conversion productivity, but also highlights the need for higher stability, efficiency, and application-oriented development (Cabau-Peinado et al., 2024; Jourdin & Burdyny, 2021).

Bioelectrochemical CO_2 Conversion Is Seen as Promising but Not Yet Production-Ready

Most participants considered microbial electrosynthesis a promising technology because it can support a shift from carbon emission control to carbon valorization. Researchers described MES as a technology that can potentially transform CO_2 from an environmental burden into a useful input for biofuel synthesis. This view appeared strongly among participants from research institutions and universities because they understood MES as a pathway that combines carbon utilization, electrochemical innovation, and microbial conversion. However, participants also stated that the technology still faces a clear gap between laboratory success and industrial reliability. One researcher explained, "The concept is strong because CO_2 is not only captured, but converted. The problem is that stable production for weeks or months is still difficult" (P03, researcher). Another participant from an industrial setting noted, "Industry will not only ask whether acetate can be produced. Industry will ask whether the system can run continuously, safely, and at predictable cost" (P11, industrial emission manager).

These statements show that the main concern was not the scientific potential of MES, but its ability to operate consistently in practical settings. Observation data supported this pattern because laboratory demonstrations showed that MES operation required careful control of pH, voltage, medium composition, gas flow, and microbial condition. Participants repeatedly linked technological readiness with operational stability rather than only with product yield. Therefore, scale-up readiness was understood as a practical condition that includes durability, process control, maintenance needs, and compatibility with industrial routines. Participants also emphasized that industrial actors need evidence from pilot-scale systems before they can consider MES as a realistic option for biofuel production. In this context, MES was not rejected as a future technology, but it was viewed as an emerging system that still requires stronger validation, longer testing periods, and clearer integration with industrial operations.

Electrode Performance and Cathodic Biofilm Stability Shape the Core Technical Bottleneck

The second finding concerns electrode material and cathodic biofilm stability, which participants viewed as the central technical bottleneck in MES development. The cathode was described as the most critical component because it functions as the interface where electron transfer, microbial colonization, and CO_2 reduction occur. Several participants stated that electrode design determines not only conversion efficiency, but also long-term performance, maintenance needs, and cost feasibility. One technician explained, "A good cathode is not only conductive. It must allow microorganisms to attach, survive, and keep working without frequent replacement" (P07, reactor technician). A microbiology expert added, “Biofilm is the living part of the system. If the biofilm collapses, the whole process becomes unstable even when the electrical setting looks correct” (P05, microbiology expert).

These statements indicate that participants understood MES as a hybrid biological and electrochemical process. They did not separate electrode optimization from microbial performance because both elements determine whether CO_2 conversion can remain stable over time. Participants also expressed concern about the availability and cost of advanced electrode materials. Several informants stated that high-performance materials may work well in experimental settings, but become difficult to justify when the system moves toward industrial scale. This concern was especially relevant in the Indonesian context because the adoption of new energy technologies often depends on material availability, maintenance capacity, and investment feasibility. This finding aligns with studies that identify cathodic biofilms as essential for MES and cathode development as a major determinant of CO_2 conversion performance (Ibrahim et al., 2023; Vassilev et al., 2022).

Scale-Up Depends on Reactor Design, Gas-Liquid Transfer, and Continuous Operation

The third finding shows that participants associated MES scale-up with reactor configuration, gas-liquid transfer, and continuous operational control. They argued that laboratory success often depends on small-volume systems where operating conditions can be controlled closely by researchers or technicians. When the system becomes larger, new problems may emerge, including uneven gas distribution, pH gradients, biofilm detachment, higher internal resistance, and energy losses. One participant stated, “In a small reactor, CO_2 delivery can be controlled easily. In a larger reactor, the question is whether all active zones receive enough CO_2 and electrons at the same time” (P02, electrochemical researcher). Another participant explained, “Scale-up is not just making the reactor bigger. It changes the behavior of the whole system” (P09, process engineer).

These views show that scale-up was understood as a redesign process rather than a simple increase in reactor volume. Participants also emphasized the importance of continuous operation because industrial application requires stable production, predictable output, and reliable product recovery. Batch systems were considered useful for early validation, but insufficient to prove industrial feasibility. Document analysis supported this view because recent MES studies increasingly focus on directed flow-through systems, gas diffusion biocathodes, flow reactors, and gas lift configurations. Cabau-Peinado et al. (2024) report that directed flow-through MES can improve biofilm density, current density, and productivity, which supports the participants’ view that reactor innovation is central to scale-up readiness. In addition, participants noted that future reactor development should consider not only conversion efficiency, but also cleaning procedures, energy demand, operator safety, and the ability to connect with industrial CO_2 sources.

Industrial Implementation Requires Institutional, Economic, and Policy Readiness

The fourth finding indicates that MES implementation is shaped by institutional, economic, and policy factors, not only by technical performance. Industrial participants stated that CO_2 conversion technologies must fit existing emission management systems, energy supply conditions, safety standards, labor capacity, and investment priorities. A participant from an industrial area explained, “Factories already have emission control systems. A new technology must show where it connects, who operates it, and how the product will be used” (P13, industrial practitioner). A policy-related informant added, “If the technology supports biofuel and carbon reduction, policy can help. But the evidence must be clear, especially on cost, efficiency, and environmental benefit” (P16, policy actor). These statements show that participants interpreted MES as a socio-technical innovation rather than a standalone reactor technology.

Its future adoption depends on collaboration among universities, national research institutions, industrial operators, and government agencies. Participants also noted that Indonesia's biofuel context remains strongly connected with land-based feedstock, especially biodiesel. Therefore, CO_2-based biofuel pathways may offer a complementary strategy, but not an immediate replacement for existing systems. Participants emphasized that pilot-scale demonstration, techno-economic evaluation, life-cycle assessment, and policy incentives are needed before MES can be positioned as a realistic industrial biofuel pathway. They also argued that industrial areas such as Cilegon and Karawang can become relevant locations for future pilot projects because these areas provide access to potential CO_2 sources and industrial users. In this sense, the implementation of MES requires not only scientific progress, but also institutional coordination, financial support, regulatory clarity, and market readiness for CO_2-derived biofuel products.

4. Conclusions

This study concludes that bioelectrochemical enhancement for scalable CO_2 conversion in biofuel synthesis should be understood as both a technical and socio-technical process. The findings show that microbial electrosynthesis is viewed as a promising pathway for connecting CO_2 utilization, renewable electricity, and biofuel precursor production. However, its readiness for industrial application remains limited by several key challenges, including long-term process stability, electrode performance, cathodic biofilm resilience, gas-liquid mass transfer, reactor configuration, and continuous operation. The study also shows that technological readiness cannot be measured only by product yield or laboratory success. It must also include operational reliability, cost feasibility, maintenance capacity, industrial compatibility, and policy support.

Theoretically, this study contributes to the literature by expanding the understanding of microbial electrosynthesis from a reactor-based technology into a socio-technical system shaped by actors, institutions, infrastructure, and regulatory context. Practically, the findings suggest that future development should prioritize pilot-scale testing, durable and affordable electrode materials, stable cathodic biofilm systems, and integration with industrial CO_2 sources. From a policy perspective, support is needed through research funding, demonstration projects, carbon utilization incentives, and clear standards for CO_2-derived biofuel products. Future studies should combine qualitative inquiry with techno-economic analysis and life-cycle assessment to evaluate the feasibility, environmental impact, and adoption potential of MES in different industrial and national contexts.

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