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A comprehensive review on biotechnological carbon capture and utilization using engineered microorganisms: technical foundations, reactor systems, and industrial perspectives

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Abstract

Carbon capture and utilization (CCU) is emerging as a critical technology pathway for reducing greenhouse gas emissions while producing value–added fuels, chemicals, proteins, and materials. Unlike conventional carbon capture and storage, which primarily focuses on isolating CO_2 from industrial emissions for geological storage, biotechnological CCU employs microorganisms as living catalytic platforms to convert CO_2 or carbon–rich waste gases into commercially useful products. Engineered microorganisms, including acetogenic bacteria, cyanobacteria, and hydrogen–oxidizing microbes, can be modified through synthetic biology and metabolic engineering to enhance carbon fixation efficiency, product selectivity, and overall process performance. From a technical perspective, microbial CO_2 fixation relies on natural metabolic pathways such as the Calvin–Benson–Bassham cycle and the Wood–Ljungdahl pathway. These pathways can be optimized or redesigned using synthetic biology approaches to improve carbon assimilation and enable targeted synthesis of fuels and commodity chemicals. In particular, acetogenic bacteria convert CO_2 and CO into Acetyl–CoA via the Wood–Ljungdahl pathway, providing a key intermediate for downstream biochemical production. Advances in systems biology, pathway engineering, and bioprocess design have significantly improved the scalability and robustness of these microbial systems, supporting their role in emerging circular carbon economies. Despite major technological advances, significant challenges related to reactor scalability, gas–liquid mass transfer, energy demand, and downstream processing continue to limit large–scale industrial deployment of microbial CCU systems. Market growth in CCU technologies is driven by global net–zero commitments, industrial decarbonization efforts, carbon pricing mechanisms, and increasing demand for sustainable fuels and materials. Carbon capture, utilization, and storage (CCUS) is widely recognized as a key pathway for decarbonizing hard–to–abate sectors such as aviation, cement, and steel. The global CCUS market is estimated at approximately USD 5.82 billion in 2025 and is projected to reach USD 17.75 billion by 2030, while the CCU market alone is expected to grow from USD 3.60 billion in 2025 to USD 5.34 billion by 2031. This study proposes a comparative techno–economic framework to evaluate microbial CCU systems relative to conventional carbon capture and storage technologies. Unlike many previous reviews focused primarily on microbial metabolism or carbon fixation pathways, this study integrates biological, engineering, and techno–economic perspectives to evaluate the industrial feasibility and scalability of microbial CCU technologies. The review provides a comprehensive overview of microbial carbon fixation pathways, engineered microbial platforms, reactor systems, commercialization trends, and future technological directions for sustainable carbon biomanufacturing.

Keywords: microbial carbon capture and utilization, carbon dioxide fixation, synthetic biology, metabolic engineering, gas fermentation, microbial electrosynthesis, photobioreactors, acetogenic bacteria, cyanobacteria, microalgae, Wood–Ljungdahl pathway, Calvin–Benson–Bassham cycle, carbon biorefineries, renewable biomanufacturing, techno–economic analysis

Abbreviations: ATP, adenosine triphosphate; C1, one–carbon; CBB, Calvin–Benson–Bassham; CCS, carbon capture and storage; CCU, carbon capture and utilization; CCUS, carbon capture utilization, and storage; CFD, computational fluid dynamics; CO, carbon monoxide; CO_2, carbon dioxide; kLa, volumetric gas–liquid mass transfer coefficient; MES, microbial electrosynthesis; NADPH, nicotinamide adenine dinucleotide phosphate (reduced form); PBR, photobioreactor; PHA, polyhydroxyalkanoate; PHB, polyhydroxybutyrate; rGlyP, reductive glycine pathway; rTCA, reverse tricarboxylic acid cycle; RuBP, ribulose–1,5–bisphosphate; RuBisCO, ribulose–1,5–bisphosphate carboxylase/oxygenase; SAF, sustainable aviation fuel; STR, stirred–tank reactor; WL pathway, wood–Ljungdahl pathway

Introduction

Global carbon dioxide (CO_2) emissions have exhibited a sustained increase in recent years, as depicted in Figure 1,[1] highlighting the urgency of developing effective carbon mitigation strategies. Anthropogenic CO_2 emissions remain a primary driver of climate change, largely originating from energy production, industrial processes, and transportation sectors. Despite significant advances in renewable energy technologies, emissions from hard–to–abate industries such as cement, steel, and aviation continue to pose substantial challenges to achieving global net–zero targets.[2] Carbon capture, utilization, and storage (CCUS) technologies have therefore gained increasing attention as essential components of climate mitigation strategies, enabling the reduction of atmospheric CO_2 while supporting continued industrial activity.[2]

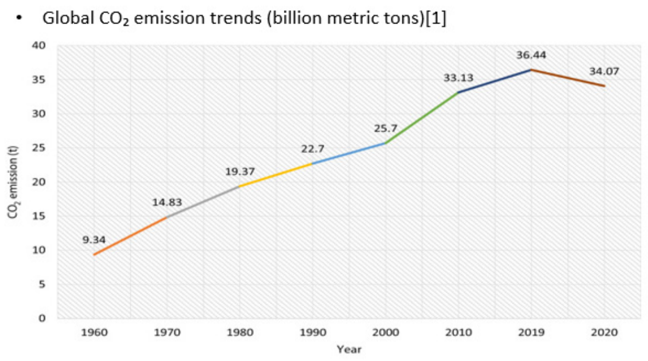

Figure 1 Global CO_2 emission trends (billion metric tons)[1]

The Figure shows the increasing trend of global carbon dioxide emissions over recent decades, highlighting the continued rise in anthropogenic greenhouse gas emissions associated with industrialization, fossil fuel consumption, and energy production.

While conventional carbon capture and storage (CCS) technologies focus primarily on capturing CO_2 emissions and storing them in geological formations, they are often associated with high operational costs, energy penalties, and long–term storage uncertainties. The energy required for CO_2 capture, compression, and transport can significantly reduce overall process efficiency, increasing the economic burden of CCS deployment.[2] In addition, CCS does not generate direct economic value from captured carbon, which can limit its large–scale industrial adoption.

As a result, increasing attention has shifted toward carbon capture and utilization (CCU), which seeks to convert captured CO_2 into value–added products such as fuels, chemicals, and materials. Recent advances in biochemical CO_2 conversion technologies have demonstrated the feasibility of transforming CO_2 into useful products through biological and catalytic pathways.[3] By integrating carbon capture with product generation, CCU offers a pathway toward improved resource utilization and supports the development of sustainable and circular carbon economies.[2,3]

Biotechnological carbon capture and utilization leverages the metabolic capabilities of microorganisms to convert CO_2 or carbon–rich waste gases into valuable products. Microorganisms such as cyanobacteria, acetogenic bacteria, and hydrogen–oxidizing microbes possess natural carbon fixation pathways that enable the assimilation of CO_2 into organic compounds.[1,4] These biological systems operate under relatively mild conditions compared to thermochemical processes, offering advantages in terms of energy efficiency and process selectivity. Advances in synthetic biology and metabolic engineering have enabled the modification of these microorganisms to enhance carbon fixation rates, redirect metabolic fluxes, and improve product yields.[1,5] In particular, acetogenic bacteria utilize the Wood–Ljungdahl pathway to convert CO_2 and CO into acetyl–CoA, a central intermediate for the synthesis of fuels and commodity chemicals.[6] Similarly, photosynthetic organisms such as cyanobacteria employ the Calvin–Benson–Bassham cycle to fix CO_2 using light energy, providing an alternative route for sustainable carbon conversion.[5] These developments highlight the potential of engineered microbial systems as versatile platforms for carbon utilization in industrial applications.

Despite significant advances in microbial carbon capture and utilization technologies, several technical and engineering challenges continue to limit their large–scale implementation. One of the primary constraints is the relatively low efficiency of natural carbon fixation pathways, where key enzymes such as RuBisCO exhibit limited catalytic rates and susceptibility to competitive reactions, thereby restricting overall carbon assimilation performance.[5] In addition, the thermodynamic and energetic requirements of CO_2 reduction impose further limitations, often necessitating substantial energy input to sustain microbial conversion processes.[3]

At the bioprocess level, gas–liquid mass transfer remains a critical bottleneck, as the low solubility of CO_2 in aqueous media limits its availability to microbial cells and reduces overall conversion efficiency.[7] These limitations become more pronounced during scale–up, where maintaining efficient gas transfer, microbial activity, and product yield in large–scale bioreactors presents significant challenges.[7,8] Furthermore, the introduction of engineered metabolic pathways can lead to cellular stress, metabolic imbalance, and accumulation of toxic intermediates, ultimately reducing system stability and productivity.[1,4,6] From an industrial perspective, further constraints arise from reactor design, process optimization, and downstream separation. The transition from laboratory–scale systems to industrial deployment requires improvements in energy efficiency, operational stability, and overall process economics, particularly because enhancing gas–liquid mass transfer often increases energy demand.[8] Although microbial carbon capture and utilization (CCU) systems have shown promising technological progress, scalability and techno–economic feasibility remain major barriers to their widespread adoption.[9]

In this context, there is a growing need for comprehensive analyses that integrate biological performance with engineering constraints and economic feasibility. While previous studies have extensively explored microbial carbon fixation pathways and metabolic engineering strategies,[1,6] fewer have systematically evaluated these advances from a combined techno–economic and process engineering perspective. In particular, the scalability of microbial CCU systems remains insufficiently addressed, especially when considering reactor design, energy requirements, and market–driven constraints.[9] Accordingly, this review presents an integrated analysis of market size, growth trends, and major industry participants in the field of carbon capture and utilization across the United States, European Union, and global markets. It further examines companies operating at pilot, pre–commercial, and early commercialization stages, highlighting emerging technological developments and competitive dynamics. This analysis is subsequently complemented by a detailed discussion of the underlying technical aspects of microbial CCU systems, including metabolic pathways, organism engineering strategies, and bioprocess design. By combining market insights with technical evaluation, this study aims to provide a comprehensive techno–economic perspective on the viability and future development of microbial CCU technologies.

Market size, growth, and trends

The global market for carbon capture, utilization, and storage (CCUS) is expanding rapidly as governments and industries increase investment in decarbonization technologies. The CCUS market is projected to grow from approximately USD 5.82 billion in 2025 to USD 17.75 billion by 2030, reflecting a compound annual growth rate (CAGR) of about 25.0%.[10] Within this broader framework, the carbon capture and utilization (CCU) segment represents a smaller but steadily growing market, estimated to increase from approximately USD 3.60–3.84 billion in 2025–2026 to around USD 5.34 billion by 2031.[11] Other market analyses similarly indicate that the CCU sector reached approximately USD 4.38 billion in 2023 and is projected to exceed USD 10 billion by 2032, highlighting its long–term growth potential.[12]

From a regional perspective, North America currently dominates the CCU market, supported by strong policy incentives such as the U.S. 45Q tax credit and large–scale investments in carbon management infrastructure. The United States has announced hundreds of carbon capture projects and continues to lead in both industrial deployment and innovation. In contrast, the European Union market is driven primarily by regulatory frameworks, including the EU Green Deal, the Carbon Border Adjustment Mechanism, and the Industrial Carbon Management Strategy, which collectively promote carbon capture, utilization, and storage across energy–intensive sectors.

Within the broader CCU landscape, biotechnological or microbial CCU represents an emerging sub–sector focused on the biological conversion of CO_2 into fuels, chemicals, and proteins. Although precise market segmentation for microbial CCU remains limited due to its early–stage development, it is generally categorized within gas fermentation and biological CO_2 conversion technologies.[3,6] This approach leverages engineered microorganisms to convert carbon–rich gases into value–added products, including ethanol, acetate, and other platform chemicals, demonstrating potential for integration with industrial emissions and renewable energy systems.[6]

The increasing interest in microbial CCU is driven by advances in synthetic biology and metabolic engineering, which have improved carbon fixation efficiency and product selectivity.[1,4] In addition, recent studies highlight the role of biological CO_2 conversion technologies in supporting circular carbon economies and sustainable chemical production.[3] However, despite its promising potential, microbial CCU remains at a relatively low technology readiness level compared to conventional chemical CCU pathways, and its current market share is still limited. As shown in Figure 2, the CCUS market is projected to experience significantly higher growth compared to the CCU segment over the next decade.[10–12]

- Global market growth projections for CCUS and CCU technologies

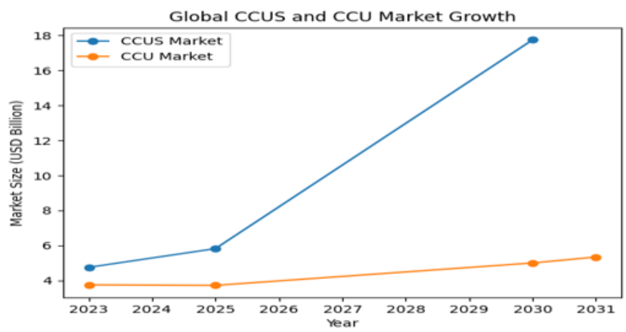

Figure 2 Global market growth projections for CCUS and CCU technologies[10–12]

The Figure shows projected market growth trends for carbon capture, utilization, and storage (CCUS) and carbon capture and utilization (CCU) technologies, illustrating expected expansion in market value and increasing industrial investment over the coming decade.

Furthermore, the regional distribution of CCU market activity is presented in Figure 3, highlighting the dominance of North America and the growing role of the European Union and Asia–Pacific regions.[10–12]

- Regional distribution of the global CCU market

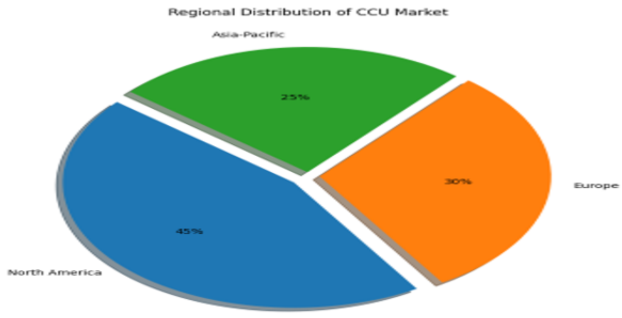

Figure 3 Regional distribution of the global CCU market[10–12]
The Figure shows the approximate regional distribution of carbon capture and utilization market activity, highlighting the dominant role of North America and the growing contributions of Europe and the Asia-Pacific region.

The key economic indicators of the CCUS and CCU markets, including market size, growth projections, and primary drivers, are summarized in Table 1 to facilitate comparison across different technological segments.

Although a clearly defined standalone market size for microbial carbon capture and utilization is not yet established, emerging analyses of bioengineering–based carbon capture technologies suggest that this segment could reach approximately USD 10 billion by 2033, with sustained double–digit growth rates driven by advances in synthetic biology and industrial biotechnology.[13,14] This category encompasses a range of biologically driven approaches, including microbial CCU, algae–based carbon capture systems, and bioreactor–based gas fermentation processes. These technologies leverage biological pathways to convert CO_2 into value–added products, offering potential advantages in terms of sustainability and process selectivity. Furthermore, increasing integration with renewable energy systems and growing demand for low–carbon fuels and chemicals are expected to further accelerate the development and commercialization of these biological carbon utilization platforms. The present and projected future development of bioengineering–based carbon capture technologies, including microbial CO_2 utilization systems, is illustrated in Figure 4.

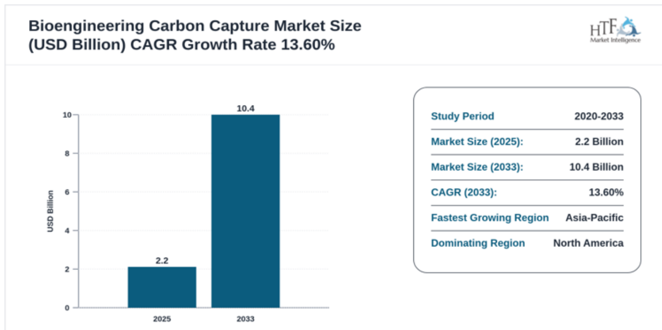

Figure 4 Projected growth of the bioengineering-based carbon capture market[13]

The Figure shows the projected expansion of bioengineering-based carbon capture technologies, including microbial carbon utilization systems, algae-based carbon capture, and biological gas conversion platforms, from 2025 to 2033.

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Table 1 Summary of global CCUS and CCU market size, projected growth, and key drivers based on recent industry analyses

Category	Market Size (2025)	Projected Size	CAGR	Key Drivers	Ref.
CCUS	USD 5.82 Bn	USD 17.75 Bn (2030)	**~25%**	Policy support, CCS deployment	10
CCU	USD 3.60–3.84 Bn	USD 5.34 Bn (2031)	**~6–7%**	Sustainable fuels, chemicals	11
CCU (alt. forecast)	USD 4.38 Bn (2023)	~USD 10.75 Bn (2032)	**~10.5%**	Long-term growth, decarbonization demand	12
Microbial CCU	Emerging	Not well-defined	**—**	Synthetic biology, gas fermentation	3,6,13,14

Note: CCUS = carbon capture, utilization, and storage; CCU = carbon capture and utilization. Market figures sourced from commercial industry reports.[10–12] Microbial CCU market data derived from emerging bioengineering-based carbon capture analyses.[3,6,13,14]

Despite the promising growth trends shown in Figure 4, the widespread commercialization of microbial CCU technologies will depend on overcoming key technical and economic challenges, including scalability, energy efficiency, and cost competitiveness.[15,16] Large–scale implementation of microbial and algae–based carbon utilization systems requires substantial improvements in bioreactor performance, CO_2 gas–liquid mass transfer, light and nutrient delivery, and downstream product recovery.[17,18] High operational costs associated with cultivation, harvesting, dewatering, drying, and energy input also remain major barriers to the economic viability of biological CO_2 conversion platforms. Emerging approaches, including microbial electrosynthesis and advanced metabolic engineering, may help address some of these limitations by improving electron utilization, carbon conversion efficiency, and product selectivity.[1,15,19] However, further advances in process integration, renewable electricity coupling, low–energy recovery methods, and industrial–scale optimization are still required to move microbial CCU systems beyond pilot–scale demonstrations toward commercially competitive deployment.

Available competitor products and companies (US & EU)

The commercial landscape for microbial carbon capture and utilization is still emerging, but several companies in the United States and Europe have developed products or platform technologies that demonstrate the industrial potential of biological CO_2 and waste–gas conversion. These companies generally operate in areas such as gas fermentation, microbial protein production, microbial oil production, and sustainable fuel precursors.

In the United States, **LanzaTech** is one of the most advanced companies in microbial CCU. Its proprietary gas fermentation platform converts industrial emissions, CO_2, and gasified waste into ethanol, which can serve as a feedstock for fuels, chemicals, and consumer products.[20] LanzaTech has also reported commercial carbon recycling projects, including a planned facility in Norway designed to produce approximately 24 kilotons of sustainable ethanol annually from furnace gas.[21] Another U.S.–based company, **Cemvita**, uses proprietary microorganisms, described as "xtremophiles," to convert carbon waste into valuable products such as sustainable oil and fuel feedstocks.[22] Cemvita has also announced partnerships related to the conversion of carbon waste into sustainable oil for sustainable aviation fuel applications.[23]

In Europe, **Solar Foods** represents a leading example of biological carbon utilization for food protein production. The Finnish company produces **Solein®**, a microbial protein made using electricity, carbon dioxide, and hydrogen. Its Factory 01 facility in Finland began commercial–scale production in 2024, marking a major milestone in the commercialization of food production from CO_2 and electricity.[24,25] Another European competitor is **Aerbio**, formerly Deep Branch Biotechnology, which is developing **Proton™**, a single–cell protein produced from CO_2 and hydrogen for animal feed applications. Aerbio launched a pilot facility in the Netherlands in 2024 capable of producing approximately 200 kg of single–cell protein per month.[26,27]

Overall, currently available competitor products are concentrated in three major product categories: ethanol and fuel precursors, microbial proteins for food or feed, and microbial oils for sustainable aviation fuel. While these technologies demonstrate commercial promise, most remain at pilot, pre–commercial, or early commercialization stages. This indicates that microbial CCU is progressing beyond laboratory research but has not yet reached the maturity or scale of conventional chemical carbon utilization technologies.

A comparative analysis of major microbial carbon capture and utilization (CCU) companies, technologies, products, and commercialization strategies is presented in Table 2. The table highlights the diversity of biological carbon conversion approaches currently under development, ranging from gas fermentation systems for sustainable fuel production to microbial protein platforms for food and feed applications. In addition, the comparison illustrates important differences in carbon sources, target markets, technological maturity, and competitive advantages among current microbial CCU platforms. Overall, Table 2 demonstrates the increasing industrial diversification of microbial carbon utilization technologies and their growing potential for commercial implementation across multiple sectors.[20–27]

Table 2 Comparative analysis of microbial carbon capture and utilization companies, technologies, products, and commercialization strategies

Company	Region	Main Technology	Carbon Source	Main Product	Target Application	Commercial Status	Key Competitive Advantage	Reference
LanzaTech	United States	Gas fermentation using engineered acetogenic bacteria	Industrial CO_2, CO, syngas	Ethanol, fuel precursors	Sustainable fuels, chemicals	Commercial / Industrial deployment	Direct utilization of industrial waste gases	20, 21
Cemvita	United States	Microbial conversion using engineered extremophiles	Carbon waste streams	Sustainable oil, SAF feedstocks	Sustainable aviation fuel	Pilot / Early commercialization	High adaptability to harsh industrial environments	22, 23
Solar Foods	Finland (EU)	Hydrogen-oxidizing microbial cultivation	$CO_2 + H_2$ + renewable electricity	Solein® microbial protein	Food and alternative protein	Commercial-scale production	Protein production independent of agriculture	24, 25
Aerbio	Netherlands (EU)	Gas fermentation / single-cell protein production	$CO_2 + H_2$	Proton™ microbial protein	Animal feed	Pilot-scale	Low-land-use protein production with carbon recycling	26, 27

Note: The table summarizes representative microbial CCU companies currently operating in fuel, chemical, food, and feed sectors. SAF = sustainable aviation fuel. Commercial status reflects information available at time of writing.

The current commercial development status of major microbial CCU companies operating in the United States and European Union is illustrated in Figure 5.

- Commercial development status of selected microbial CCU companies

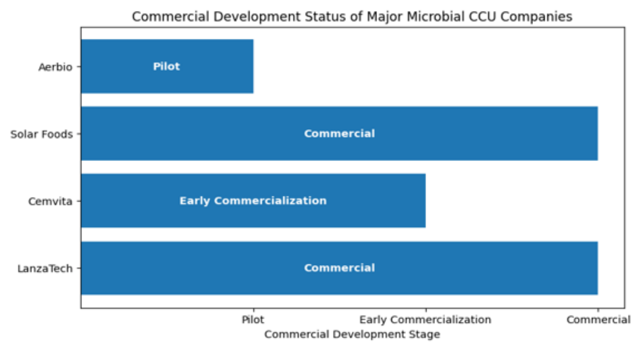

Figure 5 Commercial development status of selected microbial CCU companies[20–27]

The Figure shows the current commercialization stages of representative microbial carbon capture and utilization companies operating in fuel, chemical, food, and feed sectors, ranging from pilot-scale development to commercial deployment.

Microbial carbon fixation pathways

Microbial carbon fixation pathways constitute the biochemical core of microbial carbon capture and utilization systems, enabling microorganisms to assimilate inorganic carbon and convert it into biomass, fuels, and value–added chemicals. These pathways differ substantially in their energy requirements, enzymatic mechanisms, carbon conversion efficiencies, and industrial applicability. Among the various naturally occurring carbon fixation routes, the Calvin–Benson–Bassham cycle, the Wood–Ljungdahl pathway, and hydrogen–dependent CO_2 reduction pathways are particularly important in engineered microbial CCU systems because of their compatibility with industrial gas streams, renewable energy integration, and synthetic biology–based optimization strategies.[4,5]

The principal microbial carbon fixation pathways relevant to engineered microbial CCU systems are summarized in Figure 6, highlighting the biochemical diversity of biological CO_2 assimilation mechanisms used in industrial and emerging carbon utilization platforms.

- Major microbial carbon fixation pathways used in microbial CCU systems

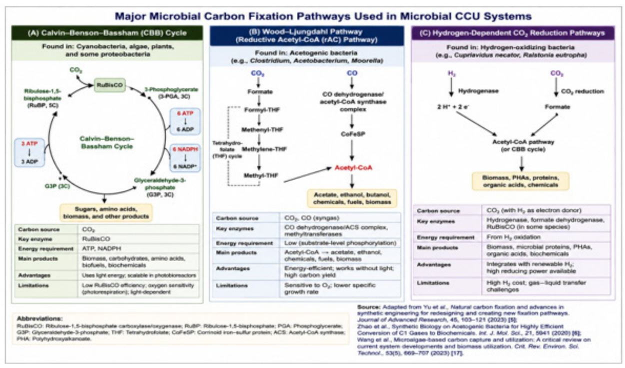

Figure 6 Major microbial carbon fixation pathways used in microbial CCU systems[5,6,17]

The Figure shows the principal biological carbon fixation pathways relevant to engineered microbial carbon capture and utilization technologies, including the Calvin–Benson–Bassham cycle, the Wood–Ljungdahl pathway, and hydrogen-dependent CO2 reduction pathways.

Calvin–benson–bassham (CBB) cycle section

The Calvin–Benson–Bassham (CBB) cycle is the most extensively studied biological carbon fixation pathway and serves as the primary mechanism for CO_2 assimilation in cyanobacteria, microalgae,

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plants, and several chemoautotrophic bacteria.[5,17] In this pathway, carbon fixation begins with the carboxylation of ribulose–1,5–bisphosphate (RuBP) catalyzed by ribulose–1,5–bisphosphate carboxylase/oxygenase (RuBisCO), generating 3–phosphoglycerate as the initial stable carbon fixation product. Subsequent enzymatic reactions regenerate RuBP while producing intermediates required for carbohydrate synthesis and cellular metabolism.

The CBB cycle is especially important in photosynthetic microbial CCU systems because it directly links solar energy capture with carbon fixation. Cyanobacteria and microalgae utilize light–driven photosynthesis to generate ATP and NADPH, which are required to sustain carbon assimilation and biomass production.[17,18] As a result, photosynthetic microbial platforms are considered attractive for sustainable fuel generation, wastewater treatment, biofertilizer production, and carbon–neutral biomass generation.

Despite its widespread occurrence, the CBB cycle suffers from several biochemical limitations. RuBisCO exhibits relatively low catalytic turnover rates and limited substrate specificity, frequently catalyzing oxygenation reactions that reduce overall carbon fixation efficiency through photorespiration.[5] Furthermore, photosynthetic systems are highly dependent on environmental conditions such as light intensity, temperature, nutrient availability, and CO_2 concentration. In large–scale photobioreactors, uneven light penetration and oxygen accumulation can significantly reduce productivity and biomass yield.[17,18]

To overcome these limitations, extensive synthetic biology and metabolic engineering strategies have been explored. These approaches include engineering RuBisCO variants with improved catalytic efficiency, introducing carbon–concentrating mechanisms, optimizing light utilization pathways, and redesigning photosynthetic metabolism to enhance carbon partitioning toward desired products.[1,4,5,28–32] Recent advances in systems metabolic engineering have also enabled the development of engineered cyanobacterial strains with improved photosynthetic productivity, stress tolerance, and carbon sequestration capacity.[32] In parallel, synthetic biology efforts are increasingly focused on redesigning native carbon fixation pathways and developing artificial or "new–to–nature" carbon assimilation routes with improved thermodynamic and energetic efficiency.[28,30] Furthermore, advances in photobioreactor engineering, automated cultivation systems, and algae harvesting technologies have improved the scalability and industrial relevance of photosynthetic microbial CCU systems.[16–18] A schematic overview of the pathway is presented in Figure 7.

- Overview of the Calvin–Benson–Bassham (CBB) cycle

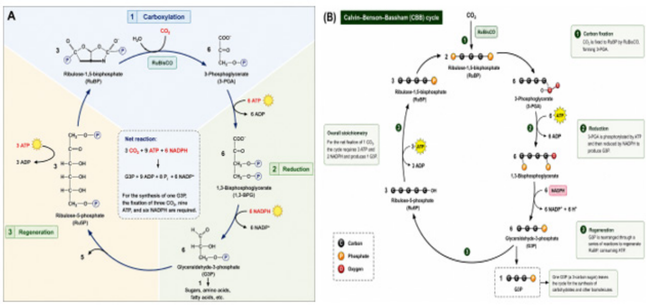

Figure 7 Overview of the Calvin–Benson–Bassham (CBB) cycle[5]

The figure shows an Overview of the Calvin–Benson–Bassham (CBB) cycle used for biological CO_2 fixation in photosynthetic microorganisms and cyanobacteria .**(A)** Simplified schematic representation of the Calvin–Benson–Bassham cycle showing the three major phases of carbon fixation, reduction, and regeneration. In this pathway, CO_2 is fixed by RuBisCO and subsequently converted into glyceraldehyde-3-phosphate (G3P) using ATP and NADPH generated through photosynthesis.**(B)** Detailed biochemical representation of the Calvin–Benson–Bassham cycle illustrating intermediate metabolites, ATP/NADPH consumption, and regeneration of ribulose-1,5-bisphosphate (RuBP). The pathway demonstrates the central role of RuBisCO-mediated CO_2 assimilation in photosynthetic carbon fixation systems.

Wood–ljungdahl pathway

The Wood–Ljungdahl pathway, also known as the reductive acetyl–CoA pathway, is a non–photosynthetic carbon fixation route primarily found in acetogenic bacteria such as *Clostridium*, *Acetobacterium*, and *Moorella* species.[6] Unlike the CBB cycle, this pathway does not rely on light energy and instead uses reducing equivalents generated from hydrogen, carbon monoxide, or syngas metabolism to convert CO_2 into acetyl–CoA.

In this pathway, one molecule of CO_2 is reduced to a methyl group through tetrahydrofolate–dependent reactions, while another CO_2 molecule is reduced to carbon monoxide by carbon monoxide dehydrogenase. These intermediates are subsequently combined by the acetyl–CoA synthase complex to generate acetyl–CoA, which serves as a precursor for acetate, ethanol, butanol, and other industrially valuable products.[6] Because acetyl–CoA is a central metabolic intermediate, the Wood–Ljungdahl pathway provides direct integration between carbon fixation and biochemical production.

The Wood–Ljungdahl pathway is considered one of the most energy–efficient natural carbon fixation mechanisms currently known.[5,6] This feature makes acetogenic bacteria highly attractive for industrial gas fermentation processes using steel mill off–gases, syngas, and industrial carbon emissions. Companies such as LanzaTech have already demonstrated commercial–scale gas fermentation systems utilizing engineered acetogens for ethanol production.[20,21]

Nevertheless, several technical challenges remain. Many acetogenic microorganisms exhibit relatively slow growth rates, strict anaerobic requirements, and sensitivity to environmental fluctuations. In addition, maintaining efficient gas–liquid mass transfer within industrial bioreactors remains difficult because of the low aqueous solubility of gaseous substrates such as CO_2 and hydrogen.[7,8] Metabolic engineering approaches are therefore being used to improve electron transfer efficiency, pathway regulation, substrate tolerance, and product selectivity in acetogenic systems.[1,6,28,29,31] Recent studies have further explored cofactor balancing, ATP optimization, and synthetic pathway redesign to enhance carbon conversion efficiency and improve the industrial robustness of acetogenic microorganisms.[28–31] The metabolic complexity and industrial relevance of the Wood–Ljungdahl pathway are illustrated in Figure 8, highlighting the integration of acetogenic carbon fixation with central carbon metabolism and engineered biochemical production pathways.[6]

Hydrogen–dependent CO2 reduction pathways

Hydrogen–dependent microbial carbon fixation pathways are increasingly recognized as promising platforms for renewable–energy–integrated CCU systems. Hydrogen–oxidizing microorganisms, including *Cupriavidus necator* and related chemolithoautotrophic bacteria, use hydrogen as an electron donor to reduce CO_2 and generate biomass or biochemical products.[15,19]

In these systems, hydrogen oxidation generates reducing power that supports carbon fixation through pathways such as the Calvin cycle or modified acetyl–CoA pathways. Because hydrogen can be produced through water electrolysis powered by renewable electricity, hydrogen–dependent microbial CCU systems create a direct link between renewable energy and biological carbon conversion.[19] This concept is particularly important for emerging microbial protein platforms and bioelectrochemical production systems.

- Metabolic overview of the Wood–Ljungdahl pathway

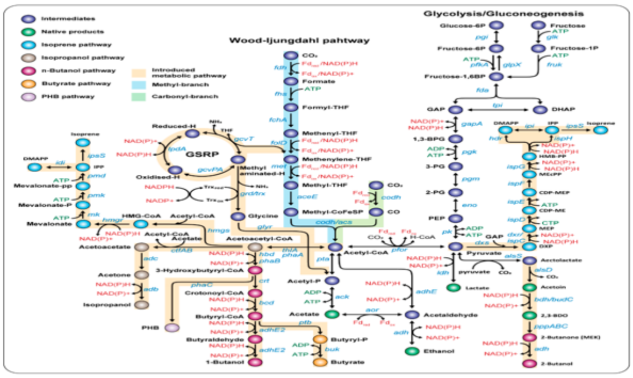

Figure 8 Metabolic overview of the Wood–Ljungdahl pathway[6]
The Figure shows a Metabolic overview of the Wood–Ljungdahl pathway integrated with central carbon metabolism and engineered biosynthetic pathways in acetogenic microorganisms. The figure illustrates the conversion of CO2 and CO into acetyl-CoA and downstream value-added products including ethanol, butanol, acetate, isopropanol, and polyhydroxybutyrate (PHB).

Hydrogen–dependent systems are gaining attention because they may achieve higher carbon conversion efficiencies than traditional photosynthetic platforms while avoiding limitations associated with light penetration in photobioreactors.[15,19] These systems also support the production of microbial proteins, polyhydroxyalkanoates (PHAs), organic acids, and sustainable chemicals using captured CO_2 as the primary carbon source.

However, large–scale implementation remains technically challenging. Hydrogen gas exhibits low solubility and presents safety concerns related to storage and transport. Efficient gas delivery, reactor pressurization, and electron transfer optimization remain major engineering bottlenecks.[7,19] In addition, the economic feasibility of these systems strongly depends on the availability of low–cost renewable electricity and green hydrogen production infrastructure.

Recent advances in microbial electrosynthesis and electro–biotechnological systems may help overcome some of these challenges by directly coupling microbial metabolism with electrochemical electron transfer systems.[15,19] These approaches are increasingly viewed as next–generation strategies for sustainable biochemical production and carbon–neutral industrial biotechnology because they enable renewable electricity to drive microbial CO_2 conversion.[19,28,29] Furthermore, synthetic biology and systems metabolic engineering are being applied to improve hydrogen utilization efficiency, electron transport pathways, and product selectivity in hydrogen–oxidizing microorganisms.[29–31] Despite these advances, achieving stable large–scale operation, low–cost hydrogen supply, and efficient reactor integration remains a major challenge for the commercialization of hydrogen–dependent microbial CCU technologies.[15,19,31,33] A schematic overview of microbial electrosynthesis and its associated biochemical production pathways is presented in Figure 9. In addition to the Calvin–Benson–Bassham and Wood–Ljungdahl pathways, several alternative natural and synthetic carbon fixation pathways have attracted increasing attention in microbial CCU research. These include the reverse tricarboxylic acid (rTCA) cycle, the 3–hydroxypropionate bicycle, and the reductive glycine pathway (rGlyP), which exhibit distinct energetic, thermodynamic, and biochemical characteristics.[5,28,30,36] Among these, the reductive glycine pathway has emerged as a particularly promising target for synthetic biology and one–carbon metabolism engineering because of its high theoretical carbon conversion efficiency and relatively low ATP demand compared with conventional fixation pathways.[30,31,34] Recent advances in synthetic pathway engineering and carbon recycling strategies have also enabled the development of artificial and "new–to–nature" carbon fixation systems designed to improve carbon assimilation efficiency and reduce energetic limitations associated with natural autotrophic metabolism.[28,30,35] Although these pathways are not yet widely implemented at industrial scale, they provide important opportunities for the future development of highly efficient engineered carbon fixation systems for microbial CCU applications.[28–36]

Schematic representation of a microbial electrosynthesis system

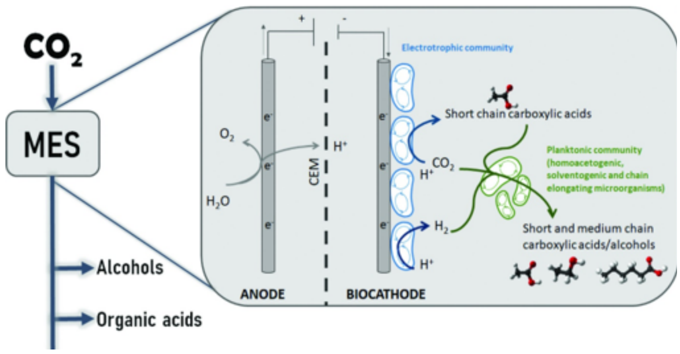

Figure 9 Schematic representation of a microbial electrosynthesis system[19]

The Figure shows a Schematic representation of a microbial electrosynthesis (MES) system for biological CO2 reduction using electroactive microbial communities. Electrons generated through electrochemical reactions are transferred to microorganisms at the biocathode, enabling the conversion of CO2 into short-chain carboxylic acids, alcohols, and other value-added biochemicals. The figure also illustrates hydrogen-mediated electron transfer and the integration of homoacetogenic and chain-elongating microorganisms within MES platforms.

Engineered microorganisms for microbial CCU

Engineered microorganisms are central to microbial carbon capture and utilization because they provide the biological platforms through which CO_2, CO, syngas, or hydrogen–derived reducing power can be converted into fuels, chemicals, polymers, proteins, and biomass. The most relevant microbial platforms for CCU include acetogenic bacteria, cyanobacteria, microalgae, and hydrogen–oxidizing microorganisms. Each platform has distinct metabolic advantages, product spectra, engineering strategies, and scale–up limitations. Therefore, selecting an appropriate organism depends on the carbon source, energy input, target product, reactor configuration, and intended industrial application.[1,3,5,29]

Acetogenic bacteria

Acetogenic bacteria are among the most industrially advanced microbial platforms for carbon utilization because they can convert CO, CO_2, and H_2 into acetyl–CoA through the Wood–Ljungdahl pathway. This allows acetogens to use industrial off–gases, syngas, and carbon–rich waste streams as feedstocks for the production of acetate, ethanol, and other reduced biochemicals.[6,37] Representative acetogenic hosts include *Clostridium autoethanogenum*, *Clostridium ljungdahlii*, and *Acetobacterium woodii*, which have been widely investigated for gas fermentation applications.

Among these organisms, Clostridium autoethanogenum is particularly important because it has become a model gas–fermenting acetogen for industrial carbon recycling. Recent advances in synthetic biology tools, genome editing, and metabolic engineering have improved the ability to modify acetogenic metabolism, redirect carbon flux, and enhance the production of biochemicals from C1 gases.[37] These engineering strategies are essential because native acetogenic metabolism often favors acetate formation, while industrial applications may require higher selectivity toward ethanol, butanol, acetone, or other value–added products. The complex electron transfer reactions and energy conservation mechanisms involved in acetogenic gas fermentation are illustrated in Figure 10, highlighting the central role of ferredoxin cycling, hydrogenases, and the Wood–Ljungdahl pathway in acetogenic carbon metabolism.

- Electron transfer and energy conservation mechanisms in acetogenic bacteria

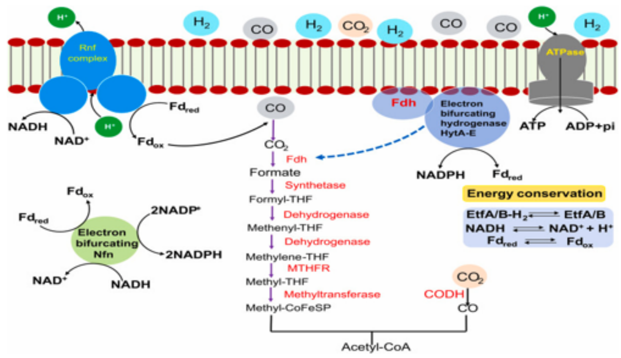

Figure 10 Electron transfer and energy conservation mechanisms in acetogenic bacteria[37]

The Figure shows a Schematic representation of electron transfer and energy conservation mechanisms associated with the Wood–Ljungdahl pathway in acetogenic bacteria. The figure illustrates the roles of the Rnf complex, Nfn complex, hydrogenases, ferredoxin-dependent reactions, and tetrahydrofolate-mediated C1 metabolism during the conversion of CO_2, CO, and H_2 into acetyl-CoA in engineered acetogenic systems.

However, acetogenic systems remain technically challenging. Many acetogens grow slowly, require strict anaerobic conditions, and are sensitive to pH, gas composition, and redox balance. In addition, gas–liquid mass transfer limitations reduce the availability of CO_2, CO, and H_2 to microbial cells, thereby constraining productivity at large scale.[7,8] Despite these limitations, acetogenic bacteria currently represent one of the most commercially mature microbial CCU platforms, as demonstrated by industrial gas fermentation technologies such as those developed by LanzaTech.[20,21]

Cyanobacteria

Cyanobacteria are photosynthetic prokaryotes capable of directly fixing CO_2 using light energy through the Calvin–Benson–Bassham cycle. Because they combine carbon fixation, photosynthesis, and genetic tractability, cyanobacteria are considered promising microbial chassis for sustainable production of biofuels, bioplastics, organic acids, and specialty chemicals.[5,32] Unlike acetogens, cyanobacteria do not require organic carbon sources or external hydrogen supply, instead, they use solar energy to generate ATP and reducing equivalents for CO_2 assimilation.

Metabolic engineering of cyanobacteria has focused on improving photosynthetic efficiency, redirecting carbon flux from biomass formation toward target products, increasing tolerance to product toxicity, and enhancing carbon–concentrating mechanisms.[32,38,39] Recent developments in molecular biology tools, metabolic models, and fast–growing cyanobacterial strains have expanded their potential for carbon–negative biomanufacturing and CO_2–based production systems.[32] These advances are especially relevant for applications where direct conversion of CO_2 into bioproducts is desired without the need for sugar–based feedstocks.

Nevertheless, cyanobacterial CCU still faces major scale–up barriers. Low areal productivity, high infrastructure costs, light penetration limitations, contamination risks, and environmental sensitivity remain important constraints for outdoor cultivation and large photobioreactor systems.[32,38,39] As a result, cyanobacteria are scientifically attractive but less commercially mature than gas–fermenting acetogens.

Microalgae

Microalgae represent another major photosynthetic platform for biological carbon capture and utilization. They can assimilate CO_2 through photosynthesis while generating biomass rich in lipids, carbohydrates, proteins, pigments, and other value–added compounds.[17,18] Compared with many terrestrial crops, microalgae can exhibit high growth rates, do not necessarily require arable land, and can be cultivated using saline water, wastewater, or flue–gas–derived CO_2 streams, making them attractive for integrated carbon utilization and biomass production systems.[17] In microbial CCU, microalgae are especially relevant for biofuel production because lipid–rich biomass can be processed into biodiesel or other fuel precursors. They are also valuable for producing animal feed, nutraceuticals, fertilizers, bioplastics, and wastewater treatment products.[17,18] Engineering approaches include strain selection, adaptive laboratory evolution, lipid pathway modification, improvement of light utilization, and optimization of harvesting and downstream processing.[16–18] Despite these advantages, microalgal CCU systems face persistent economic and engineering limitations. Harvesting, dewatering, drying, nutrient supply, contamination control, and photobioreactor operation can significantly increase production costs.[16–18] Therefore, although microalgae have strong potential for integrated carbon capture and biomass utilization, large–scale commercialization depends on improving cultivation efficiency, reducing downstream processing costs, and developing higher–value coproduct strategies. The cultivation, harvesting, and downstream processing stages associated with microalgae–based carbon capture and biofuel production are illustrated in Figure 11, highlighting the major harvesting approaches and their relative performance in terms of energy efficiency, cost, and biomass quality.[16]

Hydrogen–oxidizing microorganisms

Hydrogen–oxidizing microorganisms, particularly *Cupriavidus necator*, are increasingly important in microbial CCU because they can use H_2 as an electron donor and CO_2 as a carbon source for autotrophic growth. *C. necator* is a chemolithoautotrophic model organism that can grow using H_2, O_2, and CO_2 and has been investigated for the production of polyhydroxyalkanoates, single–cell protein, bulk chemicals, and other bioproducts.[40,41] This platform is highly relevant to renewable–energy–integrated CCU because green hydrogen produced through electrolysis can provide the reducing power required for biological CO_2 conversion.One of the strongest advantages of *C. necator* is its metabolic versatility. It can grow under heterotrophic, mixotrophic, or autotrophic conditions and naturally accumulates polyhydroxybutyrate as a carbon and energy storage polymer.[40,41] Recent developments in synthetic biology, genome–scale modeling, and physiology–informed engineering have made *C. necator* increasingly attractive as a chassis for sustainable biomanufacturing from CO_2 and hydrogen.[41] However, hydrogen–oxidizing platforms also face major engineering challenges. Gas fermentation with $H_2/O_2/CO_2$ mixtures requires careful safety management because of explosion risks, and low gas solubility can limit productivity in aqueous bioreactors.[40,41] Efficient reactor design, gas delivery, pressurization, and process control are therefore essential for industrial deployment. While hydrogen–oxidizing microorganisms are promising for microbial protein, bioplastic, and chemical production, their commercial feasibility will depend strongly on access to low–cost renewable hydrogen and safe scalable reactor systems. The metabolic versatility of hydrogen–oxidizing microorganisms such as *Cupriavidus necator* is illustrated in Figure 12, highlighting the integration of autotrophic, heterotrophic, and mixotrophic metabolism with hydrogen oxidation, CO_2 fixation, and polyhydroxyalkanoate biosynthesis.[40]

- **Overview of microalgae cultivation and harvesting strategies**

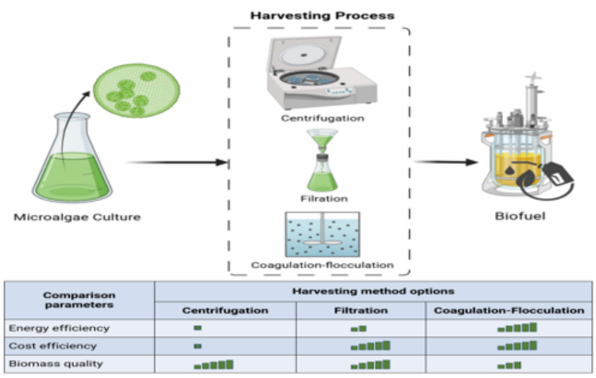

Figure 11 Overview of microalgae cultivation and harvesting strategies[16]
The Figure shows the major cultivation, harvesting, and downstream processing strategies used in microalgae-based carbon capture and biofuel production systems, including centrifugation, filtration, and coagulation–flocculation approaches.

- Metabolic overview of Cupriavidus necator

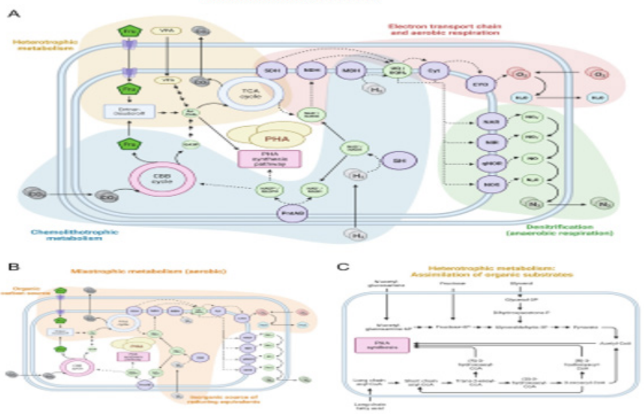

Figure 12 Metabolic overview of Cupriavidus necator[40]

The Figrue shows a Metabolic overview of *Cupriavidus necator* illustrating multiple metabolic modes associated with hydrogen oxidation, carbon assimilation, respiratory metabolism, and polyhydroxyalkanoate (PHA) biosynthesis for microbial carbon capture and utilization applications. **(A)** Comprehensive metabolic network of *Cupriavidus necator* showing the integration of chemolithotrophic, heterotrophic, and respiratory metabolism with the Calvin–Benson–Bassham (CBB) cycle, hydrogen oxidation, electron transport systems, denitrification pathways, and PHA biosynthesis.**(B)** Simplified representation of mixotrophic metabolism in *C. necator* under aerobic conditions, illustrating the simultaneous utilization of inorganic reducing equivalents and organic carbon substrates for carbon fixation and bioproduct formation.**(C)** Schematic representation of heterotrophic substrate assimilation and polyhydroxyalkanoate biosynthesis pathways in *C. necator*, highlighting the conversion of organic substrates into acetyl-CoA and downstream PHA production intermediates.

Comparative perspective sentence

Therefore, future microbial CCU development will likely rely on platform–specific optimization rather than a single universal organism. Combining metabolic engineering, reactor design, and techno–economic evaluation will be essential for identifying the most suitable microorganism for each industrial application.[1,17,19,29,32,41]

Bioreactor and process engineering systems

Bioreactor and process engineering play a critical role in determining the technical feasibility, scalability, and economic performance of microbial carbon capture and utilization (CCU) systems. Although advances in synthetic biology and metabolic engineering have significantly improved microbial carbon fixation and biochemical production capabilities, industrial deployment ultimately depends on maintaining efficient gas transfer, energy utilization, microbial productivity, and process stability at large scale.[7,8,17–19,42–47] Reactor configuration strongly influences CO2 availability, mixing behavior, light distribution, nutrient transport, electron transfer efficiency, and downstream processing requirements. Consequently, bioreactor design remains one of the central engineering challenges in the commercialization of microbial CCU technologies.[7,8,16–19,42–47]

Microbial CCU systems employ a wide range of reactor configurations depending on the metabolic characteristics of the microorganisms involved and the target products being generated. Photosynthetic systems such as cyanobacteria and microalgae are commonly cultivated in photobioreactors or open pond systems that enable light–driven carbon fixation.[17,18,42–47] In contrast, acetogenic gas fermentation platforms typically utilize stirred–tank reactors, bubble columns, airlift reactors, or trickle–bed systems optimized for gas–liquid mass transfer and anaerobic operation.[6–8,37] More recently, microbial electrosynthesis platforms have introduced bioelectrochemical reactor systems in which microorganisms directly or indirectly receive electrons from electrodes to support CO_2 reduction and biochemical synthesis.[15,19,33]

The performance of these reactor systems depends heavily on process engineering parameters such as gas–liquid mass transfer coefficients (kLa), reactor hydrodynamics, mixing intensity, shear stress, temperature control, pH regulation, nutrient availability, and energy consumption.[7,8,45–47] In biological CO_2 conversion systems, poor gas solubility often limits substrate availability and reduces microbial productivity, particularly during scale–up.[7,8] Similarly, photosynthetic reactors face additional constraints related to light attenuation, oxygen accumulation, biofilm formation, and uneven photon distribution.[17,18,42–47] Therefore, reactor optimization is essential not only for improving carbon conversion efficiency but also for reducing operational costs and improving industrial viability.

In recent years, increasing integration of renewable electricity, electrochemical systems, advanced sensor technologies, computational fluid dynamics (CFD)–based optimization, and automated process control has expanded the engineering possibilities for microbial CCU bioprocesses.[15,19,42,46,47] These developments have enabled more sophisticated approaches for controlling electron transfer, gas utilization, light management, and metabolic performance in large–scale systems. Nevertheless, significant engineering barriers remain, particularly in relation to reactor scalability, energy efficiency, process intensification, and downstream product recovery. Accordingly, understanding the advantages and limitations of different reactor systems is essential for evaluating the future industrial potential of microbial CCU technologies.[7,17,19,42–47]

Photobioreactors

Photobioreactors (PBRs) are specialized cultivation systems designed for the growth of photosynthetic microorganisms such as cyanobacteria and microalgae under controlled environmental conditions. These systems provide light, CO_2, nutrients, and mixing to support photosynthetic carbon fixation and biomass production.[17,18,42,47] A generalized schematic of an integrated photobioreactor–based CCU system is illustrated in Figure 13, highlighting the coupling of CO_2 utilization, wastewater remediation, biomass harvesting, and downstream conversion into multiple value–added products.[42] Compared with open pond cultivation systems, photobioreactors offer improved environmental control, reduced contamination risk, higher biomass productivity, and enhanced CO_2 utilization efficiency. As a result, PBRs are widely investigated for microbial carbon capture, biofuel production, wastewater treatment, and high–value biochemical synthesis.[42–44] Photobioreactor (PBR) systems are becoming central to sustainable microalgae–based processes, linking renewable energy production, environmental remediation, and industrial biotechnology. Microalgae can fix CO_2 at high rates. *Chlorella vulgaris* achieves 0.49 g CO_2 L^{-1} d^{-1} under 5 % CO_2 aeration in bubble column PBRs,[48] while *Nannochloropsis gaditana* reaches 1.7 g CO_2 L^{-1} d^{-1} in tubular systems supplied with 8 % CO_2.[49]

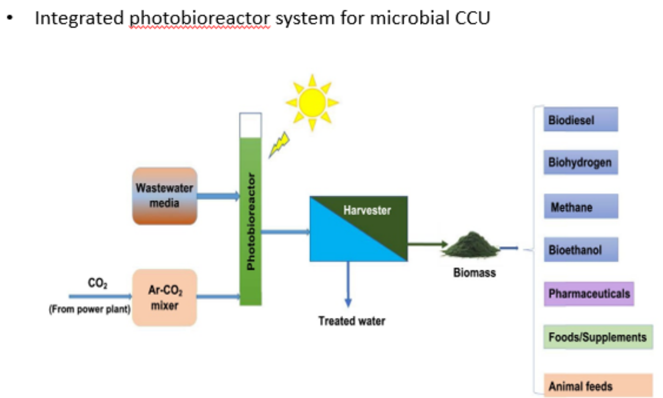

Figure 13 Integrated photobioreactor system for microbial CCU[42] The Figure shows a schematic representation of an integrated photobioreactor-based carbon capture and utilization system incorporating microalgal cultivation, industrial CO2 utilization, wastewater remediation, biomass harvesting, and downstream conversion into biofuels, food supplements, pharmaceuticals, and animal feed products.

Several photobioreactor configurations have been developed, including tubular photobioreactors, flat–panel photobioreactors, bubble–column systems, airlift photobioreactors, and hybrid reactor designs. Tubular systems provide high surface–area–to–volume ratios that improve light exposure and photosynthetic efficiency, whereas flat–panel systems often exhibit superior light distribution and gas transfer performance.[17,42,47] Bubble–column and airlift photobioreactors are additionally attractive because they improve circulation and mixing while minimizing shear stress on sensitive microalgal cells.[18,46] The selection of reactor configuration depends strongly on the target microorganism, cultivation scale, environmental conditions, and desired product.

Despite their advantages, photobioreactors face substantial engineering and economic challenges. One of the major limitations is light attenuation caused by increasing cell density during cultivation. As biomass concentration increases, light penetration becomes increasingly uneven, leading to reduced photosynthetic efficiency and lower productivity.[17,42,47] Oxygen accumulation generated during photosynthesis can also inhibit cellular metabolism and contribute to oxidative stress. Furthermore, maintaining temperature control, nutrient delivery, and efficient CO_2 transfer in large–scale systems requires substantial energy input and process optimization.[18,43,46]

Recent advances in photobioreactor engineering have focused on improving light management, hydrodynamic performance, computational fluid dynamics (CFD)–based optimization, automation, and process integration.[42,46,47] Novel reactor materials, internal illumination systems, optical fiber–assisted light delivery, and advanced monitoring systems are increasingly being explored to enhance scalability and reduce operational costs.[42,46] In addition, integration of photobioreactors with industrial flue gas streams, direct air capture systems, and wastewater treatment processes has attracted significant interest as a strategy for improving economic feasibility and environmental sustainability.[42–45] However, despite ongoing engineering improvements, large–scale photobioreactor deployment remains constrained by high capital costs, operational complexity, contamination risks, and energy–intensive downstream biomass processing.[16–18,42–47]

Gas fermentation bioreactors

Gas fermentation bioreactors are among the most important reactor systems in microbial carbon capture and utilization because they enable the biological conversion of gaseous carbon sources such as CO_2, CO, syngas, and H_2 into fuels and value–added chemicals using acetogenic microorganisms [6–8,37,50,53]. These systems are particularly attractive for industrial CCU applications because they can directly utilize industrial off–gases generated from steel manufacturing, petroleum refining, waste gasification, and chemical production processes.[50] Through microbial gas fermentation, carbon–rich gaseous waste streams can be biologically converted into ethanol, acetate, butanol, organic acids, and other commercially valuable products.[6,37,50] The performance of gas fermentation systems depends strongly on reactor configuration and gas–liquid mass transfer efficiency. Since gases such as CO_2, CO, and H_2 exhibit relatively low solubility in aqueous media, efficient gas transfer from the gas phase into the liquid culture medium becomes a major engineering challenge.[7,8,51,52] Consequently, reactor design plays a central role in determining substrate availability, microbial productivity, mixing behavior, and overall process economics. Important engineering parameters include gas holdup, bubble size distribution, agitation speed, pressure, interfacial surface area, and volumetric mass transfer coefficients (kLa).[7,51,52] Inadequate gas transfer can significantly reduce microbial growth rates and carbon conversion efficiency, particularly during large–scale continuous fermentation processes.[51,52] A generalized overview of industrial gas fermentation systems used in microbial carbon capture and utilization is illustrated in Figure 14, highlighting the integration of syngas fermentation, renewable hydrogen utilization, acetogenic biocatalysts, and the production of natural and recombinant biochemicals from industrial carbon sources.[50]

- Gas fermentation pathways for microbial carbon capture and utilization

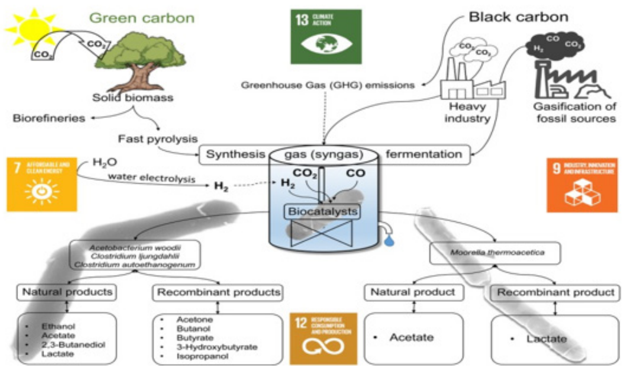

Figure 14 Gas fermentation pathways for microbial carbon capture and utilization[50]

The Figure shows a Schematic representation of gas fermentation pathways for microbial carbon capture and utilization using acetogenic microorganisms and syngas-derived substrates. The figure illustrates the integration of industrial CO2 emissions, renewable hydrogen, syngas generation, acetogenic biocatalysts, and downstream production of natural and recombinant chemicals including ethanol, acetate, lactate, butanol, acetone, and isopropanol. Representative microorganisms include *Clostridium autoethanogenum*, *Clostridium ljungdahlii*, *Acetobacterium woodii*, and *Moorella thermoacetica.*

Several reactor configurations have been investigated for microbial gas fermentation applications, including stirred–tank reactors (STRs), bubble–column reactors, airlift reactors, and trickle–bed reactors.[6–8,51] Stirred–tank reactors are among the most widely used systems because they provide effective mixing, precise process control, and relatively high gas transfer rates through mechanical agitation and gas sparging.[7,51] However, large–scale STR operation often requires substantial energy input, particularly under high agitation conditions needed to improve gas dispersion and reduce mass transfer limitations. Bubble–column reactors are widely studied as an alternative because they provide efficient gas distribution with lower energy consumption compared with mechanically agitated systems.[6,7,51] In these reactors, gas bubbles introduced at the bottom of the column provide both substrate delivery and liquid circulation. Bubble–column systems are particularly attractive for anaerobic acetogenic fermentation because of their relatively simple design, low maintenance requirements, and reduced shear stress on microbial cells.[51] Similarly, airlift reactors improve circulation through density differences generated between riser and downcomer regions, thereby enhancing mixing and gas transfer while minimizing mechanical complexity.[7,51] Trickle–bed reactors have also attracted attention for gas fermentation processes because they provide high gas–liquid interfacial surface area and support immobilized microbial biofilms.[8] In these systems, liquid media trickle over packed solid materials while gas flows through the reactor bed, promoting enhanced substrate transfer and microbial attachment. Biofilm–based gas fermentation systems can improve cell retention, reactor stability, and volumetric productivity.[8,52] However, channeling, clogging, and uneven liquid distribution remain important operational challenges in large–scale trickle–bed systems.Recent advances in gas fermentation engineering have focused on improving mass transfer efficiency, reactor hydrodynamics, process intensification, and scale–up performance.[7,51–53] Strategies such as microbubble generation, elevated–pressure operation, membrane–based gas delivery, advanced sparger systems, and computational fluid dynamics (CFD)–guided reactor optimization have been investigated to overcome gas transfer limitations and improve microbial productivity.[7,51,52] Additionally, integration of renewable hydrogen with acetogenic fermentation has expanded the potential for sustainable CO_2 utilization and low–carbon biochemical production.[15,19,50] Despite significant progress, large–scale gas fermentation systems continue to face substantial engineering and economic barriers. Low gas solubility, high energy requirements for agitation and gas compression, contamination risks, reactor fouling, and process instability can reduce industrial feasibility.[7,8,51–53] Furthermore, maintaining stable anaerobic conditions and efficient microbial activity during continuous long–term operation remains challenging at commercial scale. Therefore, continued advances in reactor engineering, process control, microbial optimization, and integrated gas utilization strategies will be essential for improving the scalability and economic competitiveness of industrial gas fermentation technologies. An example of a continuous cell–recycled gas fermentation reactor used for CO fermentation is illustrated in Figure 15, highlighting the integration of gas delivery, pH control, membrane–assisted cell retention, and continuous medium circulation for enhanced microbial productivity.[54]

- Cell-recycled continuous bioreactor system for CO fermentation

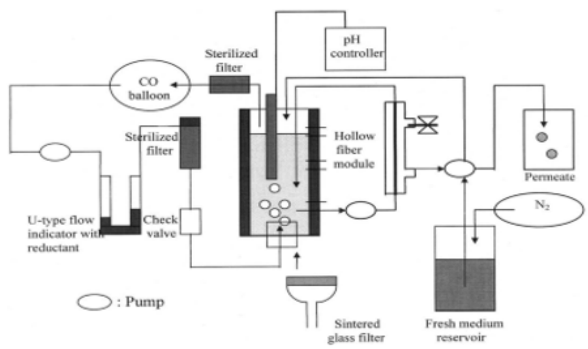

Figure 15 Cell-recycled continuous bioreactor system for CO fermentation[54]

The Figure shows a continuous cell-recycled gas fermentation reactor incorporating gas delivery systems, pH control, membrane-assisted cell retention, and continuous medium circulation for enhanced microbial productivity during acetogenic CO fermentation processes.

Microbial electrosynthesis (MES) and bioelectrochemical reactor systems

Microbial electrosynthesis (MES) has emerged as a promising next–generation platform for microbial carbon capture and utilization by integrating electrochemical systems with microbial metabolism to convert CO_2 into value–added chemicals and fuels using renewable electricity.[15,19,33,55,56] In MES systems, electroactive microorganisms utilize electrons supplied directly or indirectly from cathodes to reduce CO_2 and synthesize multicarbon compounds including acetate, methane, ethanol, butyrate, and other organic products.[15,19,56] Unlike conventional gas fermentation systems that primarily rely on gaseous substrates such as syngas or hydrogen, MES technologies introduce an electrochemical interface that enables more precise control of electron delivery and carbon reduction processes.[19,33,55] Bioelectrochemical reactor systems used in MES generally consist of anodic and cathodic chambers separated by ion–exchange membranes or membrane–less reactor configurations depending on system design.[15,19] A generalized schematic of microbial electrosynthesis and bioelectrochemical reactor configurations is illustrated in Figure 16, demonstrating electron transfer pathways, anodic and cathodic reactions, membrane and membrane–less reactor designs, and the integration of renewable electricity sources for microbial CO_2 conversion.[55] At the cathode, electroactive microorganisms or microbial biofilms receive reducing equivalents either through direct electron transfer from electrode surfaces or indirectly through electrochemically generated intermediates such as hydrogen or formate.[19,55] Simultaneously, oxidation reactions occurring at the anode complete the electrical circuit and maintain electron flow throughout the system. Reactor performance depends strongly on electrode materials, cathode surface area, electrical conductivity, membrane characteristics, electrolyte composition, reactor hydrodynamics, and microbial attachment efficiency.[15,19,57]

- Generalized microbial electrosynthesis and bioelectrochemical reactor configurations

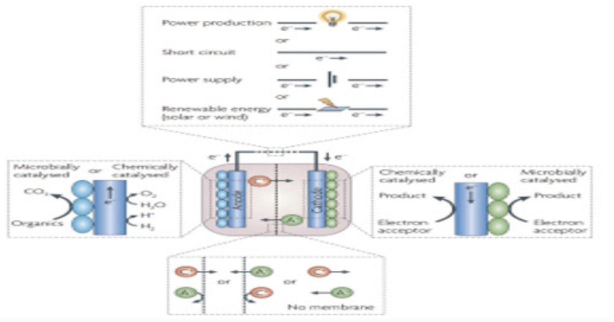

Figure 16 Generalized microbial electrosynthesis and bioelectrochemical reactor configurations[55]

The Figure shows a Generalized schematic representation of microbial electrosynthesis (MES) and bioelectrochemical reactor systems. The figure illustrates anodic and cathodic compartments, microbial and chemically catalyzed electrode reactions, electron transfer pathways, ion transport mechanisms, membrane and membrane-less configurations, and the integration of external electricity sources including renewable energy for microbial CO_2 conversion and product synthesis.

Several microbial species have demonstrated electrosynthetic capabilities, including *Sporomusa ovata*, *Clostridium ljungdahlii*, *Acetobacterium woodii*, and methanogenic archaea.[15,19,33,58] Many of these microorganisms utilize the Wood–Ljungdahl pathway for autotrophic carbon fixation, allowing efficient conversion of one–carbon substrates into acetyl–CoA–derived products.[6,15] Recent advances in synthetic biology and metabolic engineering have expanded the product spectrum of MES systems by improving electron uptake efficiency, carbon fixation rates, and metabolic flux toward desired target compounds.[15,33,56]

Electron transfer mechanisms represent one of the most critical engineering and biological aspects of MES systems. Direct electron transfer involves physical contact between microbial cells and conductive electrode surfaces, whereas indirect transfer relies on soluble mediators such as hydrogen, formate, or redox–active compounds generated electrochemically.[19,55] Improving extracellular electron transfer efficiency remains a major research priority because inefficient electron transport can significantly limit microbial productivity and overall carbon conversion rates. Consequently, substantial effort has been directed toward developing advanced cathode materials including carbon felt, graphite granules, graphene–based composites, carbon nanotubes, stainless steel meshes, and nanostructured conductive surfaces to improve microbial attachment and electron transport.[57] Recent studies have also explored surface modification strategies and nanomaterial–based electrodes to enhance biofilm formation, catalytic activity, and long–term reactor stability.[57] Mass transfer limitations also remain major engineering challenges in MES reactor systems. Efficient CO_2 delivery, proton transport, electrolyte circulation, and stable biofilm formation are essential for maintaining high electrosynthesis efficiency.[7,19] Furthermore, reactor scale–up introduces additional complications associated with internal resistance, uneven current distribution, membrane fouling, electrode degradation, and increased energy consumption.[19,33,56] Computational fluid dynamics (CFD)–guided optimization, three–dimensional electrode architectures, advanced membrane materials, and flow–through cathode systems are increasingly being investigated to improve reactor performance and industrial scalability.[56,57] Advanced microbial electrosynthesis reactor configurations incorporating proton exchange membranes (PEMs), electrocatalytic systems, and photocatalytic–assisted electron transfer mechanisms are illustrated in Figure 17, highlighting modern engineering strategies for improving CO_2 reduction efficiency and value–added chemical production.[57] One of the major advantages of MES technology is its compatibility with renewable electricity sources such as solar and wind energy, allowing direct coupling between renewable power generation and biological carbon conversion.[15,19,55] This integration offers the potential for sustainable electrobiorefineries capable of converting industrial CO_2 emissions into carbon–neutral fuels and chemicals. In addition, MES systems may contribute to long–term energy storage by converting intermittent renewable electricity into stable liquid products with higher energy density.[19,56] Despite substantial scientific progress, microbial electrosynthesis technologies remain at relatively early stages of industrial development. Low product titers, slow electron transfer rates, high electrode costs, membrane instability, and limited reactor scalability continue to restrict commercial implementation.[15,19,56–58] Furthermore, maintaining stable microbial biofilms and preventing contamination during long–term continuous operation remain major operational challenges.[58] Therefore, continued advances in electrochemical engineering, microbial metabolism, electrode material science, and reactor design will be essential for improving the techno–economic feasibility and industrial scalability of MES–based microbial carbon capture and utilization systems.

- Comparison of electron transfer mechanisms in MES systems

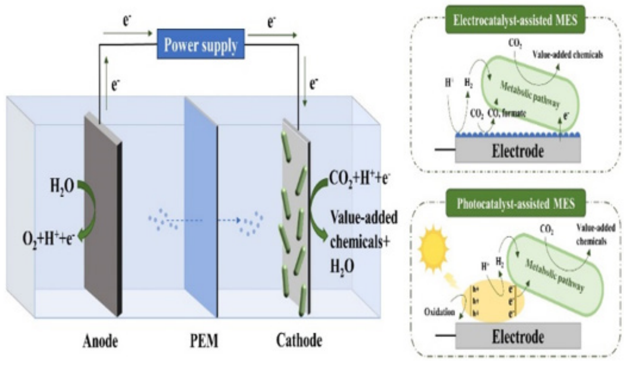

Figure 17 Comparison of electron transfer mechanisms in microbial electrosynthesis systems[56,57]

The Figure shows a Schematic representation of advanced microbial electrosynthesis (MES) reactor systems incorporating proton exchange membranes (PEMs), electrocatalyst-assisted MES, and photocatalyst-assisted MES configurations. The figure illustrates anodic water oxidation, cathodic microbial CO2 reduction, electron and proton transfer pathways, and the integration of electrochemical and photochemical energy inputs for the production of value-added chemicals.

The major microbial CCU reactor platforms discussed in Section 6 are compared in Table 3 to summarize their operational principles, advantages, limitations, products, and industrial potential.

Table 3 Comparative overview of major microbial CCU reactor systems

Reactor system	Main Microbial Platform	Carbon / Electron Source	Main Products	Key Advantages	Major Limitations	References
Photobioreactors	Microalgae, cyanobacteria	CO2 + light	Biomass, lipids, biodiesel precursors, proteins, pigments	Direct photosynthetic CO2 fixation, integration with wastewater treatment, suitable for high-value products	Light attenuation, oxygen accumulation, contamination risk, high harvesting cost, large land demand	[16–18], [42–49]
Gas Fermentation Bioreactors	Acetogenic bacteria (C. autoethanogenum, C. ljungdahlii, A. woodii)	CO, CO2, H2, syngas, industrial off-gases	Ethanol, acetate, butanol, acetone, isopropanol, organic acids	Compatible with industrial waste gases, advanced commercial development, supports continuous operation and carbon recycling	Gas–liquid mass transfer limitations, anaerobic operation, gas composition variability, reactor fouling, energy demand	[6–8], [37], [50–54]
Microbial Electrosynthesis (MES) Reactors	Electroactive microbes, acetogens, methanogens	CO2 + electrons from cathode, indirect H_2/ formate transfer possible	Acetate, methane, ethanol, butyrate, organic acids, alcohols	Direct coupling with renewable electricity, potential for carbon-neutral electrobiorefineries, controllable electron supply	Low product titers, slow electron transfer, electrode cost, membrane fouling, scale-up difficulty, biofilm instability	[15], [19], [33], [55–58]

Note: CCU, carbon capture and utilization; MES, microbial electrosynthesis; STR, stirred-tank reactor.

References correspond to peer-reviewed sources cited in the main text.

Techno–economic analysis and industrial challenges

Economic and engineering challenges

Despite major advances in synthetic biology, metabolic engineering, and reactor design, the large–scale commercialization of microbial carbon capture and utilization (CCU) technologies remains strongly constrained by economic and engineering limitations. Although microbial CCU systems offer promising opportunities for sustainable fuel, chemical, and protein production, their industrial competitiveness depends heavily on achieving favorable process economics, energy efficiency, reactor scalability, and long–term operational stability.[59–64] In many cases, biological carbon utilization platforms still exhibit higher production costs than conventional petrochemical processes because of expensive reactor infrastructure, renewable electricity requirements, gas delivery systems, and downstream product recovery operations.[59,60]

Energy demand represents one of the most important economic barriers in microbial CCU systems. Biological CO2 conversion processes frequently require substantial energy input for gas compression, agitation, mixing, illumination, electrochemical operation, and product purification.[7,17–19] In microbial electrosynthesis (MES) systems, electricity consumption is particularly critical because reactor performance depends strongly on current density, electrode efficiency, overpotential, and electron transfer rates.[59,62] Techno–economic analyses have demonstrated that electricity price, renewable energy availability, reactor efficiency, and product selectivity significantly influence the commercial feasibility of electrochemical and bioelectrochemical CO_2 conversion technologies.[59,62] Consequently, reducing electricity consumption and improving electron utilization efficiency remain major priorities for industrial MES development.

Gas fermentation platforms also face important engineering and economic challenges despite their increasing technological maturity. Industrial gas fermentation systems require efficient gas–liquid mass transfer, stable continuous operation, strict anaerobic conditions, and large–scale gas handling infrastructure.[50,60,61] However, gaseous substrates such as CO_2, CO, and H_2 exhibit relatively low solubility in aqueous media, often necessitating elevated gas flow rates, pressurization, or intensive mixing to maintain sufficient substrate availability for microbial growth and product formation.[7,8,63] These operational requirements can substantially increase energy consumption and process complexity during scale–up. Furthermore, reactor fouling, contamination risks, biofilm instability, and fluctuations in industrial waste–gas composition may negatively affect long–term productivity and economic performance.[60,61]

Downstream processing and product recovery also represent major contributors to overall production costs in microbial CCU systems. Separation and purification technologies including distillation, membrane filtration, biomass harvesting, dewatering, solvent extraction, and chromatography can account for a substantial fraction of total operational expenditures, particularly in dilute biological production systems.[16–18] In microalgae–based platforms, harvesting and drying steps are especially energy–intensive and remain major economic bottlenecks.[16,17] Similarly, low product titers in gas fermentation and MES systems often require complex and energy–demanding purification strategies.[60,64] Therefore, improving product concentration, selectivity, and integrated recovery technologies remains essential for enhancing industrial feasibility.

Reactor scalability remains another major challenge limiting the commercialization of microbial CCU technologies. Although laboratory–scale systems frequently demonstrate promising carbon conversion efficiencies and product yields, maintaining similar performance at industrial scale is substantially more difficult.[7,8,63] Large–scale systems face increasing complications associated with reactor hydrodynamics, gas transfer limitations, uneven light distribution, membrane fouling, electrode degradation, contamination control, and process stability.[17–19,42–47] In addition, the high capital costs associated with photobioreactors, electrochemical systems, gas fermentation infrastructure, and automated process control can further limit commercial deployment.[42,56,62]

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Nevertheless, recent industrial developments indicate growing commercial potential for microbial carbon utilization technologies. Industrial pilot–scale demonstrations have shown the feasibility of carbon–negative biochemical production using engineered acetogenic gas fermentation systems.[61,64] Companies such as LanzaTech have successfully integrated microbial gas fermentation with industrial waste–gas recycling processes for ethanol and chemical production.[20,21,60] Similarly, increasing investment in renewable electricity, green hydrogen infrastructure, microbial protein production, and electrobiorefinery systems continues to accelerate the development of sustainable biological carbon utilization platforms.[19,24–27] However, achieving widespread industrial adoption will require continued advances in reactor engineering, process intensification, renewable energy integration, and systems–level optimization to improve both economic competitiveness and operational scalability.[59–64] The major techno–economic and engineering barriers affecting the industrial implementation of microbial carbon capture and utilization technologies are summarized in Figure 18, including challenges associated with energy demand, gas–liquid mass transfer, downstream processing, reactor scalability, and overall process economics.

- Major techno-economic and engineering challenges in microbial CCU systems

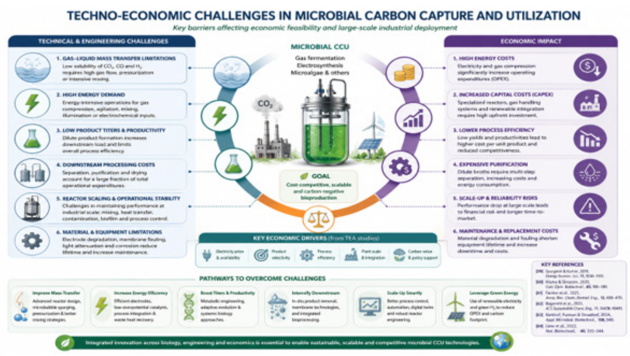

Figure 18 Major techno-economic and engineering challenges in microbial CCU systems[59–64]

The Figure shows an Overview of major techno-economic and engineering challenges associated with microbial carbon capture and utilization (CCU) systems. The figure summarizes key limitations affecting industrial deployment, including gas–liquid mass transfer constraints, high energy demand, low product titers, downstream processing costs, reactor scale-up challenges, and equipment-related limitations. In addition, major economic impacts and potential engineering strategies for improving process efficiency, sustainability, and commercial feasibility are illustrated.

Sustainability and future industrial outlook

Microbial carbon capture and utilization technologies possess significant potential for supporting sustainable industrial development and circular carbon economies by converting industrial CO_2 emissions and carbon–rich waste streams into valuable fuels, chemicals, proteins, and biomaterials.[19,60,61] Unlike conventional fossil–based manufacturing systems, microbial CCU platforms can potentially reduce net greenhouse gas emissions through biological carbon recycling and integration with renewable energy infrastructure. In particular, gas fermentation and microbial electrosynthesis systems powered by renewable electricity or green hydrogen may contribute to carbon–neutral or even carbon–negative production pathways under optimized operating conditions.[59–61,64]

The long–term sustainability of microbial CCU systems depends strongly on process integration, energy source selection, and overall life–cycle performance. Coupling microbial conversion technologies with renewable electricity, waste–gas utilization, direct air capture systems, and industrial carbon recycling strategies may substantially improve environmental performance and reduce dependence on fossil–derived feedstocks.19,60 In addition, advances in systems metabolic engineering, process intensification, and reactor optimization are expected to further improve carbon conversion efficiency, product selectivity, and operational stability, thereby enhancing industrial competitiveness.[37–39,55–58]

Recent industrial demonstrations indicate growing commercial interest in biological carbon utilization technologies. Companies such as LanzaTech have demonstrated industrial–scale gas fermentation systems capable of converting industrial waste gases into ethanol and other chemicals, highlighting the feasibility of integrating microbial CCU with existing industrial infrastructure.[20,21,60,64] Increasing governmental support for decarbonization, carbon pricing policies, renewable energy deployment, and sustainable manufacturing may further accelerate commercialization efforts in the coming years. Nevertheless, continued advances in reactor engineering, renewable energy integration, process economics, and large–scale operational stability will remain essential for enabling widespread industrial adoption of microbial carbon capture and utilization technologies. Life–cycle assessment (LCA) has become an increasingly important tool for evaluating the environmental sustainability and overall carbon reduction potential of microbial carbon capture and utilization (CCU) technologies. Although microbial CCU systems offer significant promise for reducing industrial CO_2 emissions and supporting circular carbon economies, their true environmental benefits strongly depend on factors such as electricity source, hydrogen production method, reactor energy demand, downstream processing requirements, and overall process integration.[59–64] In particular, the use of renewable electricity for hydrogen generation and bioreactor operation is considered essential for achieving meaningful net carbon reductions in gas fermentation and microbial electrosynthesis systems.Several recent studies have indicated that microbial CCU platforms may substantially reduce greenhouse gas emissions compared with conventional petrochemical production routes when renewable energy integration and efficient carbon utilization are implemented.[60–64] However, energy–intensive gas compression, CO_2 capture, biomass harvesting, and downstream purification processes may offset some environmental advantages if fossil–derived energy sources are used.[59,62] In addition, large–scale deployment of microbial CCU technologies will require improvements in process efficiency, reactor scalability, and supply chain sustainability to ensure long–term environmental and economic viability.

Future perspectives and emerging technologies

Rapid advances in synthetic biology, systems metabolic engineering, electrochemical engineering, and renewable energy integration are expected to significantly accelerate the development

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of microbial carbon capture and utilization (CCU) technologies in the coming years.[29–33,65] Emerging strategies involving artificial carbon fixation pathways, engineered microbial consortia, adaptive laboratory evolution, and CRISPR–based genome engineering are increasingly being explored to improve carbon fixation efficiency, microbial robustness, substrate utilization, and product selectivity under industrial operating conditions.[29–31,65,66] In particular, recent progress in engineering cyanobacteria, acetogenic bacteria, and hydrogen–oxidizing microorganisms has demonstrated substantial potential for improving biological CO_2 conversion and expanding the range of commercially valuable fuels, chemicals, proteins, and biomaterials generated from carbon–rich waste streams.[32,37–41] Emerging strategies including AI–assisted metabolic engineering, synthetic microbial consortia, electro–fermentation systems, and integrated carbon–negative bioprocesses may substantially improve the scalability, efficiency, and industrial feasibility of next–generation microbial carbon utilization platforms.[68–73] Future developments are also expected to focus heavily on advanced reactor engineering and integrated bioprocess systems. Hybrid platforms combining microbial electrosynthesis, gas fermentation, photobioreactors, renewable electricity, and direct air capture technologies may substantially improve overall carbon utilization efficiency and process sustainability.[19,55–58] In addition, advances in electrode materials, membrane technologies, artificial intelligence–assisted bioprocess optimization, computational modeling, and automated reactor control systems may enhance reactor stability, scalability, and energy efficiency during long–term industrial operation.[42,56,57,67] Emerging developments in modular biorefinery design, advanced catalytic materials, smart sensor technologies, and digitalized process monitoring systems are also expected to improve the operational stability and industrial scalability of microbial CCU platforms. In addition, increasing integration of automation, computational modeling, and real–time data analytics may support more efficient reactor control, predictive optimization, and adaptive large–scale bioprocess management.[56,57,67] Machine learning and AI–driven predictive modeling are increasingly being investigated for optimizing metabolic pathways, reactor conditions, microbial growth, product yields, and large–scale process control in next–generation carbon biorefineries.67Despite these promising advances, several major scientific and industrial challenges still remain. Improving electron transfer efficiency, gas–liquid mass transfer, microbial tolerance, product yields, and downstream processing efficiency will continue to be critical priorities for future research and commercialization efforts.[7,33,55–58] Furthermore, achieving economically sustainable industrial deployment will require continued integration between microbial engineering, renewable energy infrastructure, industrial process optimization, and supportive environmental policies.[59–64] Nevertheless, ongoing technological innovation and increasing global interest in decarbonization strategies suggest that microbial CCU systems may play an increasingly important role in future circular carbon economies and sustainable industrial manufacturing systems. The major emerging technologies and future development strategies expected to accelerate the industrial advancement of microbial carbon capture and utilization systems are summarized in Figure 19, including advances in synthetic biology, hybrid bioprocess systems, renewable energy integration, artificial intelligence–assisted bioprocess optimization, and next–generation carbon biorefineries.[55–67]

Recent advances in synthetic biology, microbial electrosynthesis, and electro–biological hybrid systems are expected to significantly improve the scalability and industrial feasibility of microbial carbon utilization technologies (Appendix).[69–73]

- Future perspectives and emerging technologies in microbial CCU

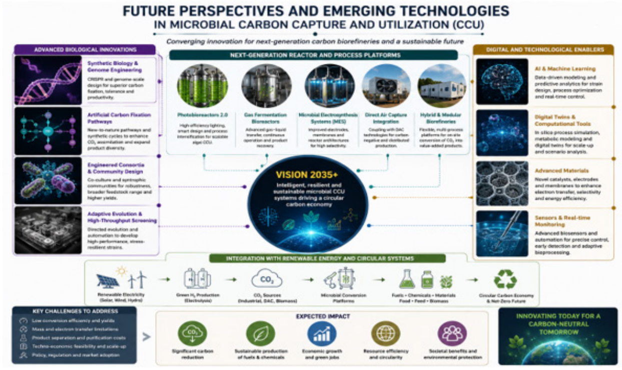

Figure 19 Future perspectives and emerging technologies in microbial CCU[55–67]

The Figure shows future development strategies and emerging technologies expected to accelerate the advancement of microbial carbon capture and utilization systems, including CRISPR-based genome engineering, artificial carbon fixation pathways, AI-assisted bioprocess optimization, hybrid electro-biological systems, renewable energy integration, and next-generation carbon biorefineries.

Conclusion

Microbial carbon capture and utilization (CCU) has emerged as a promising multidisciplinary approach for simultaneously addressing greenhouse gas emissions and sustainable biochemical production. By employing engineered microorganisms as biological catalytic platforms, microbial CCU systems enable the conversion of CO_2, syngas, and carbon–rich industrial waste gases into fuels, chemicals, proteins, biomaterials, and other value–added products under relatively mild operating conditions. Recent advances in synthetic biology, systems metabolic engineering, and bioprocess engineering have substantially improved carbon fixation efficiency, metabolic flexibility, product selectivity, and reactor performance across multiple microbial platforms including acetogenic bacteria, cyanobacteria, microalgae, and hydrogen–oxidizing microorganisms.[1,5,6,29,32]

This review has examined the major technical foundations of microbial CCU systems, including microbial carbon fixation pathways, engineered microbial platforms, and bioreactor engineering strategies. In addition, current market trends, industrial development, commercialization activities, and techno–economic challenges associated with microbial carbon utilization technologies have been evaluated from both engineering and industrial perspectives. Although substantial progress has been achieved in areas such as gas fermentation, microbial electrosynthesis, and photosynthetic carbon fixation, significant barriers related to gas–liquid mass transfer, energy demand, reactor scalability, downstream processing, and economic feasibility continue to limit large–scale industrial implementation.[7,8,15,17–19,59–64]

Nevertheless, ongoing technological innovation and increasing global interest in decarbonization, circular carbon economies, renewable energy integration, and sustainable manufacturing continue to accelerate the development of microbial CCU platforms. Emerging advances in artificial carbon fixation pathways, CRISPR–based genome engineering, AI–assisted bioprocess optimization, and hybrid electro–biological systems may further improve the scalability and industrial competitiveness of microbial carbon utilization technologies in the coming years.[29–31,55,67] Overall, microbial CCU represents a highly promising long–term strategy for sustainable carbon management and low–carbon biomanufacturing, with the potential to play an increasingly important role in future industrial biotechnology and global climate mitigation efforts. Continued integration of synthetic biology, reactor engineering, renewable energy systems, and AI–assisted optimization strategies may accelerate the transition of microbial CCU technologies from laboratory–scale research toward commercially viable carbon–negative biomanufacturing platforms.[69,71,73]

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Conflict of interest

Authors declare that there is no conflict of interest.

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