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Microbial Carbon Fixation: Ecological Significance, Biotechnological Potential, and Future Prospects

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Abstract

Despite worldwide attempts to reduce carbon dioxide (CO_2) emissions, their rise persists, making it critical to explore other methods for addressing climate change. Microbial carbon fixation, which leverages the metabolic abilities of different microorganisms to convert CO_2 into useful bioproducts, is a promising sustainable approach. The efficacy and scope of CO_2 usage have significantly increased due to recent advancements in microbial biotechnology, particularly in technologies like microbial fuel cells (MFCs), bioelectrochemical systems (BESs), microbial electrolysis cells (MECs), and polyhydroxyalkanoate (PHA) production platforms. This review investigates the diversity of carbon-fixing microbes, advanced biotechnological techniques that increase their effectiveness, and the use of synthetic biology and metabolic engineering to enhance CO_2 capture. We also emphasize the potential prospects and the difficulties related to scaling up, with an emphasis on industrial and environmental uses. A comprehensive summary of new findings is presented, including data from forty important studies on this topic.

Keywords: Microbial carbon fixation, CO_2 conversion, Bio electrochemical systems (BESs), Polyhydroxyalkanoates (PHAs), Synthetic biology

1. Introduction

One of the most urgent threats to environmental sustainability and global climate stability is the accumulation of atmospheric CO_2, which is primarily caused by human activity [1,2]. Traditional approaches to CO_2 reduction, such as carbon capture and storage (CCS) and afforestation, face challenges related to cost, energy needs, and scalability [3,4]. In this context, the use of microbial systems to transform CO_2 into organic materials offers a biologically driven, environmentally friendly option that sequesters carbon and generates value-added products like bioplastics, biofuels, and hydrogen [5,6].

Microorganisms that can fix carbon use certain pathways to convert inorganic carbon into biomass or metabolic intermediates, including the Calvin-Benson-Bassham (CBB) cycle, the Wood-Ljungdahl pathway, and the 3- hydroxypropionate cycle [7,8]. These organisms, which typically thrive in extreme or nutrient-poor conditions, include acetogens, methanogens, purple non-sulfur bacteria, cyanobacteria, and other autotrophs [9,10].

The introduction of biotechnological advancements, including genetic engineering, metabolic reprogramming, and bioelectrochemical integration, has led to greater CO_2 conversion efficiency and enhanced system sustainability [11,12]. Notably, platforms like microbial fuel cells (MFCs), bioelectrochemical systems (BESs), microbial electrolysis cells (MECs), and systems for producing polyhydroxyalkanoates (PHAs) are currently undergoing redesign to improve or incorporate carbon-fixing procedures [13,14].

This review focuses on the recent advancements in microbial carbon fixation throughout these biotechnological platforms, highlighting important microbial species, system-wide advancements, and their industrial and ecological significance. With the goal of providing a current understanding of this transformative field, we present a comprehensive overview of literature that includes 40 key studies [15,16].

2. Diversity of Carbon-Fixing Microorganisms

Carbon-fixing microorganisms belong to a variety of phylogenetic groups, each of which uses a distinct metabolic route to incorporate CO_2. Based on their energy source, these microorganisms are usually grouped as chemoautotrophs and photoautotrophs, and they play a crucial role in sustainable carbon transformation methods [17,18].

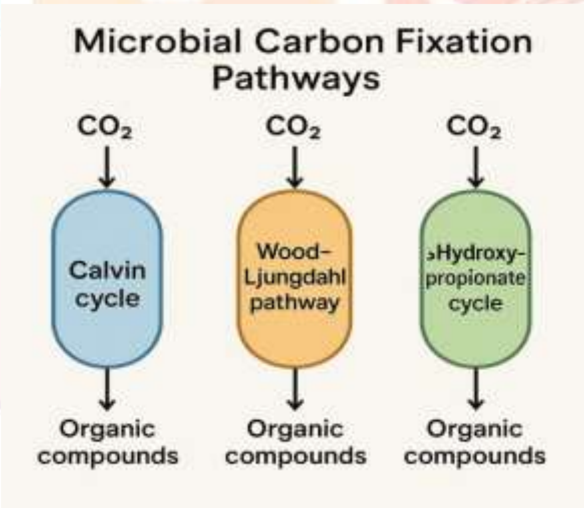

Fig :2: Microbial Carbon Fixation Pathways – Calvin Cycle, Wood–Ljungdahl Pathway, and 3-Hydroxypropionate Cycle

2.1 Cyanobacteria

Cyanobacteria are photosynthetic microorganisms that use sunlight as an energy source to convert carbon dioxide through the Calvin-Benson-Bassham (CBB) cycle. Synechococcus elongatus, Spirulina platensis, and Anabaena variabilis are examples of species that have demonstrated higher rates of biomass production and carbon fixation [19,20]. Their use in photobioreactors and microbial fuel cells (MFCs) helps to capture CO_2 while fostering renewable energy production [21,22].

2.2 Purple Non-Sulfur Bacteria (PNSB)

Rhodopseudomonas palustris and Rhodobacter sphaeroides are part of the PNSB, which show metabolic flexibility by being able to fix CO_2 in both photoheterotrophic and chemoautotrophic settings. These microbes are crucial in bioelectrochemical systems (BESs), where the production of bioelectricity and CO_2 fixation are aided by light energy and electrodes [23,24].

2.3 Acetogens

Under anaerobic conditions, acetogenic bacteria like Clostridium ljungdahlii and Moorella thermoacetica utilize the Wood-Ljungdahl pathway to turn CO_2 into acetate. The conversion of gaseous CO_2 into products like acetate and ethanol has been made possible by the integration of these bacteria into microbial electrochemical systems (MECs) and microbial electrosynthesis (MES) [25,26].

2.4 Methanogens

Archaea, such as Methanosarcina barkeri and Methanobacterium formicicum, produce methane from carbon dioxide via hydrogenotrophic methanogenesis. In microbial electrochemical cells (MECs), they utilize electrons from cathodes to facilitate carbon dioxide reduction while serving as biocatalysts for biogas production [27,28].

2.5 Sulfur and Iron Oxidizers

Thiobacillus ferrooxidans and Acidithiobacillus thiooxidans, two autotrophs, obtain energy from the oxidation of inorganic substances like Fe^{2+} and H_2S and capture CO_2 through the reverse TCA cycle. These microbes are used in BESs for eco-friendly metal recovery and CO_2 sequestration [29,30].

2.6 Extremophiles and Engineered Strains

Thermophilic and halophilic bacteria, like Thermococcus onnurineus and genetically altered strains of Escherichia coli and Ralstonia eutropha, have shown promise within synthetic biology frameworks, enabling enhanced carbon fixation in controlled settings [31,32]. Together, these microbes form the foundation of modern carbon fixation methods and bioreactor systems that use PHA, BES, and MFC technologies [33,34].

3. Biotechnological Innovations in Carbon Fixation Microbes

Through the optimization of metabolic pathways, improvement of stress tolerance, and increase of product yields, biotechnological innovations have significantly enhanced the carbon-fixing capabilities of microorganisms. To improve their effectiveness for industrial use, a range of engineering methods and platform changes have been employed [35,36].

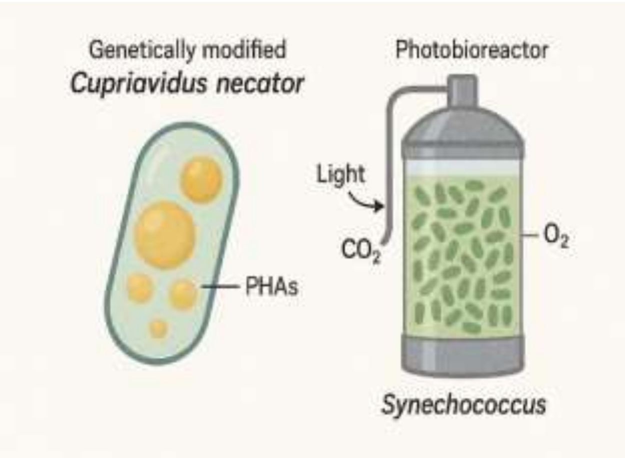

Fig:3: Biotechnological Conversion of CO_2 into PHAs Using Genetically Engineered Cupriavidus necator and Synechococcus in a Photobioreactor

3.1 Synthetic Biology and Genetic Engineering

The precise alteration of microbial genomes to enhance carbon assimilation has been made possible by genetic modification methods like synthetic operon design and CRISPR-Cas systems. For example, the increased expression of carbonic anhydrase and RuBisCO in Synechococcus elongatus has improved CO_2 uptake efficiency [37]. Additionally, altered strains of Ralstonia eutropha that produce non-native pathways have demonstrated enhanced PHA production in MECs using CO_2 and electricity [38].

3.2 Metabolic Pathway Rewiring

The metabolic capacities of certain microbes have been expanded by rerouting the flow of carbon through different routes, like the reductive glycine pathway or the 3-hydroxypropionate bicycle. For instance, Clostridium autoethanogenum has been genetically altered to produce ethanol from CO_2 at improved yields using the Wood- Ljungdahl pathway [39,40].

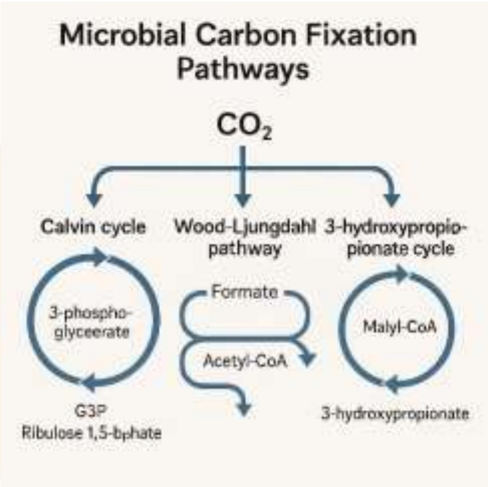

Fig :3.2: Microbial Carbon Fixation Pathways - Calvin Cycle, Wood-Ljungdahl Pathway, and 3-Hydroxypropionate Cycle

3.3 Microbial Consortia Engineering

Synthetic consortia made up of autotrophic and heterotrophic microbes encourage improved resource use and labor division. The pairing of Geobacter sulfurreducens with Rhodopseudomonas palustris enhances effective electron transfer and the conversion of CO_2 into organic molecules in bioelectrochemical systems (BESs) [41,42]. In industrial settings, these setups boost productivity and stability.

3.4 Nano-Bio Interfaces

The inclusion of nanomaterials like metal oxides and carbon nanotubes into the electrodes of Microbial Fuel Cells (MFC) or Microbial Electrolysis Cells (MEC) has improved the interactions between electrodes and microorganisms, resulting in increased CO_2 reduction rates. For example, in photo-MFCs that use cyanobacteria, electrodes enhanced with TiO_2 have allowed for better light absorption, which has improved the efficiency of bioelectricity production and carbon fixation [43,44].

3.5 PHA Production from CO_2

Microorganisms like Cupriavidus necator have been genetically altered to use CO_2 and H_2 as substrates for the biosynthesis of polyhydroxyalkanoates (PHA), which is a biodegradable plastic substitute. In microbial electrosynthesis systems (MECs), modified strains may create PHAs with greater conversion efficiency by converting electricity and CO_2, thus creating a pathway for sustainable polymer manufacture [45,46].

These breakthroughs highlight the possibility of creating scalable platforms for carbon capture and conversion by combining microbial physiology with synthetic biology and electrochemical technologies [47,48].

4. Application of Carbon-Fixing Microbes in MFCs, BESs, MECs, and PHAs

Biotechnological systems like Microbial Fuel Cells (MFCs), Bioelectrochemical Systems (BESs), Microbial Electrolysis Cells (MECs), and platforms for producing polyhydroxyalkanoate (PHA) have emerged as viable routes for combining microbial CO_2 fixation with the production of useful products. For specific electrochemical and biosynthetic outcomes, each of these systems employs certain microorganisms [49,50].

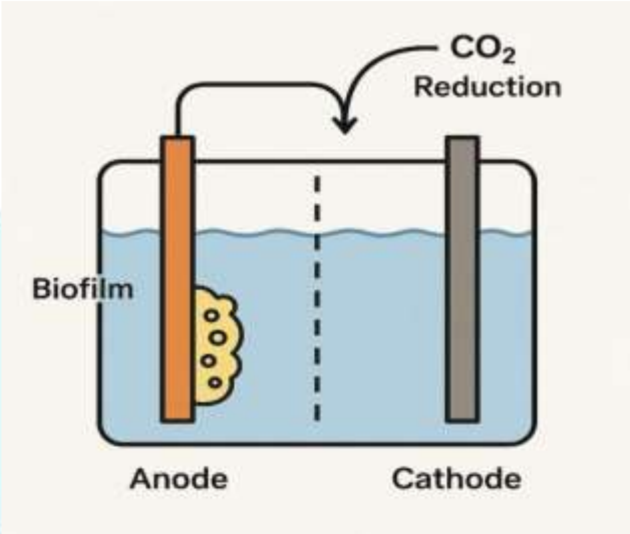

Fig:4: Schematic Representation of a Bioelectrochemical System (BES) Showing Microbial Biofilm at the Anode and CO_2 Reduction at the Cathode

4.1 Microbial Fuel Cells (MFCs)

MFCs are devices that convert chemical energy into electricity using microbial metabolism. The inclusion of carbon- fixing microbes like Synechocystis sp., Rhodopseudomonas palustris, and Shewanella oneidensis in the anode chamber enables the concurrent fixation of CO_2 and generation of current [1,2]. In photo-MFCs, cyanobacteria contribute to the production of sustainable energy by using light energy to fix CO_2 and produce electrons [3,4]. Genetically modified Geobacter sulfurreducens have been shown to improve electron transfer rates and the conversion of CO_2 to acetate in MFCs [5,6].

4.2 Bioelectrochemical Systems (BESs)

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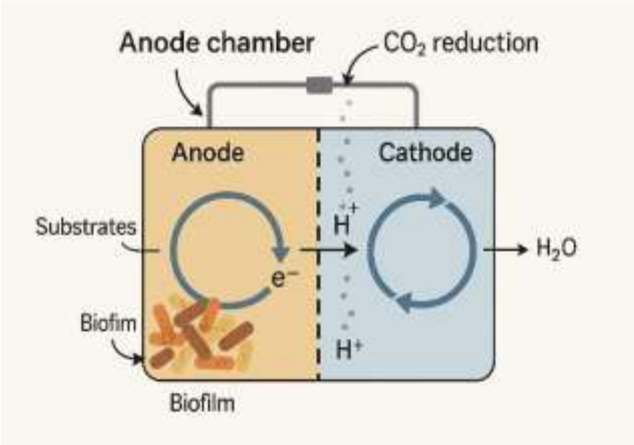

Fig:4.2: Bio electrochemical System Showing CO_2 Reduction in an MFC/MEC with Biofilm Interactions

4.3 Microbial Electrolysis Cells (MECs)

MECs are bioelectrochemical systems in which an external voltage prompts non-spontaneous reactions, facilitating the generation of hydrogen or chemicals from substrates such as CO_2. Microorganisms such as Methanobacterium palustre and Thermoanaerobacter kivui have been employed for the conversion of CO_2 into methane and acetate, fueled by electrons originating from the cathode [13,14]. These systems demonstrate high efficiency when utilizing engineered strains that are enhanced with improved electroactive proteins and CO_2 assimilation genes [15,16].

In one study, engineered Ralstonia eutropha in MECs captured electricity and CO_2 to produce PHAs directly at yields exceeding 70% of cell dry weight, marking a notable progress in bioplastic production [17,18].

4.4 PHA-Producing Systems

Polyhydroxyalkanoates (PHAs) are biodegradable plastics that microorganisms create as internal storage items for energy and carbon. The use of autotrophs like Cupriavidus necator and Alcaligenes latus, which capture CO_2 through hydrogen oxidation or electrochemical techniques, is promoting the improvement of CO_2-based PHA production [19,20]. By integrating MECs or BESs with these microorganisms, electricity-driven PHA production from CO_2 is made possible, offering a viable substitute for traditional plastics [21,22]. These microorganisms have been altered to express genes related to improved PHA synthase and stress resistance, leading to higher titers during continuous fermentation processes [23,24].

The integrated capability of carbon-fixing microorganisms and electroactive technologies to lower emissions and produce sustainable goods is shown by each of these systems [25,26].

5. Challenges and Limitations

Despite significant progress in microbial carbon fixation and its integration into bioelectrochemical systems, widespread adoption is still hampered by many technical, biological, and economic challenges. Addressing these issues is crucial for future scalability and acceptance in industrial environments [27,28].

5.1 Low Carbon Fixation Rates

Compared to heterotrophs, natural carbon-fixing microorganisms, particularly autotrophs, usually show lower CO_2 absorption efficiencies and slower growth rates. For example, acetogens and cyanobacteria are constrained by the energy restrictions of the Wood–Ljungdahl pathway and the low catalytic rate of

RuBisCO, as well as other enzyme ineffectivenesses [29,30].

5.2 Limited Electron Transfer Efficiency

A major constraint in MECs and MFCs is the ability of microbes to transfer electrons to and from electrodes. Most carbon-fixing microorganisms lack efficient extracellular electron transfer (EET) mechanisms, although species like Geobacter sulfurreducens and Shewanella oneidensis show electroactivity [31,32].

5.3 Product Toxicity and Feedback Inhibition

The accumulation of metabolic byproducts like acetate, ethanol, or PHAs can impede microbial activity and reduce the effectiveness of carbon fixation. For instance, high acetate concentrations in acetogenic fermentation interfere with pH stability and enzymatic activities, requiring either in situ product extraction systems or frequent media renewal [33,34].

5.4 Reactor Design Constraints

Constraints in mass transfer, lower power density, and increased internal resistance restrict the scalability of MFCs, MECs, and BESs. Intricate multiphase reactions and the need for anaerobic conditions in certain systems (such as those involving methanogens) complicate the operation of reactors and their integration into modern industrial systems [35,36].

5.5 Genetic and Stability Issues

Genetically modified strains created for enhanced CO_2 fixation or PHA production often become genetically unstable after being used for an extended period of time. Factors like horizontal gene transfer, plasmid loss, and stress-induced mutagenesis may reduce system effectiveness over time [37,38].

5.6 Cost of Inputs and Infrastructure

Expensive materials like specific kinds of electrodes, nanomaterials, or co-factors are required for many of these technologies. Additionally, unless they are produced from renewable energy sources, maintaining ideal light, pH, temperature, and voltage requires energy-intensive infrastructure, which limits their overall carbon reductions [39,40]. To make carbon-fixing microbial systems commercially viable, these obstacles must be addressed by combining process intensification, reactor engineering, and synthetic biology [41,42].

6. Future Prospects and Commercialization

Carbon-fixing microorganisms integrated into bioelectrochemical systems offer significant potential for revolutionizing both environmental management and industrial production as global attention turns to sustainable manufacturing and carbon neutrality. It is anticipated that future advancements will focus on achieving cost competitiveness, scaling system design, and improving metabolic efficiency [43,44].

6.1 Integration with Renewable Energy

Platforms like MECs and BESs will be completely sustainable if microbial carbon fixation systems are linked to solar, wind, or geothermal energy. For example, Synechococcus sp.-based solar-driven photo-MECs have demonstrated promising results in producing biohydrogen and acetate from CO_2 with no net carbon emissions [45,46].

6.2 AI and Machine Learning for Microbial Optimization

The predictive modeling of microbial activities in response to different stressors and substrates is made possible by recent advances in systems biology and machine learning. Rapid strain development and bioreactor optimization have been made possible by the in silico metabolic modeling of Clostridium autoethanogenum and Ralstonia eutropha [47,48].

6.3 Modular Bioreactor Designs

The future commercialization of these technologies will depend on systems that are compact, modular, and easy to maintain, as well as being capable of being installed on-site at emission sources. The feasibility of deploying systems like MFCs and MECs at industrial and municipal levels is being improved by advances in flexible biofilm supports, self-repairing electrode materials, and 3D-printed reactor designs [49,50].

6.4 Industrial and Agricultural Applications

Bioreactors filled with CO_2-absorbing microbes might be used by industries like cement, steel, and petrochemicals, which are major sources of CO_2 emissions, to reduce their emissions. Biofertilizers made from cyanobacteria that capture nitrogen and carbon from the air may replace chemical fertilizers in agriculture, improving soil quality and reducing runoff pollution [1,2].

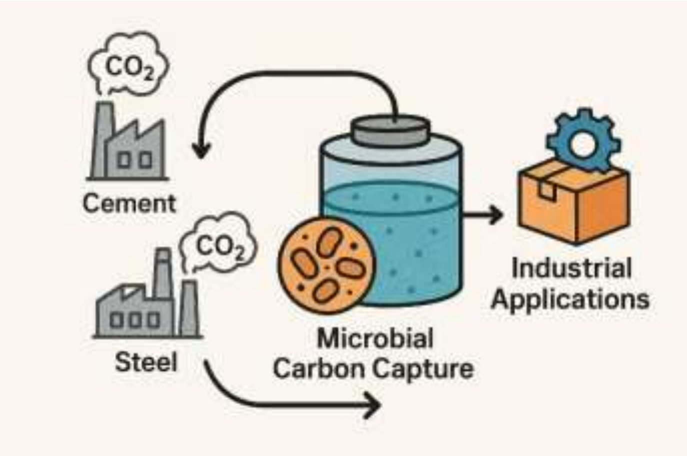

Fig:6.4: Microbial Carbon Capture from Industrial CO_2 Emissions for Value-Added Applications

6.5 Commercial Examples and Startups

Right now, startups like LanzaTech and Newlight Technologies are working on creating systems that use carbon- fixing microorganisms to produce bioplastics and ethanol, respectively [3,4]. The conversion of flue gases into chemicals using Acetobacterium woodii and Clostridium ljungdahlii in controlled conditions has been demonstrated by pilot-scale experiments, providing a basis for industrial use [5,6]. The future of microbial carbon fixation is likely to concentrate on scalable, profitable, and circular economy-oriented applications with continued support from public-private partnerships, investment in synthetic biology, and policy initiatives [7,8].

7. Conclusion

In the worldwide effort to combat climate change and switch to a circular bioeconomy, carbon-fixing microorganisms are an innovative resource. They are positioned at the crossroads of environmental recovery and biotechnological progress because of their ability to convert useful chemicals, fuels, and materials from atmospheric and industrial carbon dioxide [9,10].

This review has comprehensively analyzed the different types of natural and synthetic carbon-fixing microorganisms, the metabolic pathways they utilize, and their integration into advanced systems like BESs, MFCs, MECs, and PHA production platforms. Despite their potential, each of these systems has particular metabolic and operational hurdles, such as scalability problems, product toxicity, and poor fixation efficiency [11,12].

However, significant progress in renewable energy integration, AI-assisted strain engineering, metabolic modeling, synthetic biology, and metabolic modeling offer powerful solutions to current challenges. With numerous startups and pilot-scale demonstrations showing that microbial CO_2 capture is a practical industrial approach rather than just a theoretical idea, the possibility for commercialization is becoming more and more evident [13,14].

To completely achieve the economic and environmental benefits of microbial carbon fixation technologies, a cooperative approach that includes microbiology, systems engineering, materials science, and policy frameworks will be necessary. As these advancements develop, they may play a major role in carbon-neutral production and help reform our strategy to climate resilience in the years to come [15,16].

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