

Biological Capture and Utilization of Carbon Dioxide

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Abstract: Environmental problems associated with carbon dioxide (CO₂) make it increasingly urgent to reduce both atmospheric CO₂ concentrations and anthropogenic emissions. Efficient microbial capture provides a potentially effective route for CO₂ mitigation and utilization, mainly through autotrophic and heterotrophic pathways. This paper reviews the fundamental mechanisms and representative technologies of these two pathways, including algal photobioreactors, engineered heterotrophic microorganisms, and microbial electrosynthesis. The principal technical barriers to industrial application are analyzed, including the low catalytic activity of key carbon-fixation enzymes, the complexity and limited efficiency of natural pathways, and inadequate energy utilization. Potential development directions are also discussed, such as screening or designing high-activity carboxylases, constructing shorter synthetic carbon-fixation pathways, introducing carbon-concentrating mechanisms, and integrating electricity or hydrogen as alternative energy carriers.

Keywords: Carbon Dioxide; Biological Capture; Microbial Carbon Fixation; Carbon Capture, Utilization and Storage; Synthetic Biology.

1. Introduction

With the continued development of human society, environmental issues have received increasing attention. Greenhouse-gas emissions are widely regarded as an important contributor to the rise in global temperature, commonly referred to as the greenhouse effect. They may also be associated with sea-level rise, ocean acidification, wildfires, floods, tropical storms, and disruption of ecosystems [1-3]. Among greenhouse gases, CO₂ has attracted the greatest attention. According to a study reported by the Intergovernmental Panel on Climate Change in 2007, CO₂ accounted for 76.7% of global greenhouse-gas emissions, and the increase in atmospheric CO₂ concentration is therefore considered closely related to global warming [1,4]. Fossil-fuel combustion is one of the major contributors to CO₂ emissions. A 2015 study estimated that 87% of anthropogenic CO₂ emissions originated from the combustion of fossil fuels [4,5]. Other emission sources include land-use change, biomass utilization, transportation fuels, waste treatment and disposal, agricultural activities, residential and commercial activities, and various industrial processes [1]. In summary, the adverse environmental changes associated with increasing CO₂ concentration result from the combined effects of fossil-fuel use, industrial operation, and broader human activity.

Effective mitigation of the environmental problems caused by rising CO₂ concentrations requires both a reduction in fossil-fuel consumption through greater development and utilization of clean renewable energy and the removal of CO₂ already present in the atmosphere. Carbon capture and storage (CCS) was proposed for this purpose, with CO₂ captured to reduce atmospheric concentration and then stored for long-term isolation. Numerous physical, chemical, and biological approaches have been proposed for carbon capture [6,7]. These approaches can be broadly divided into six categories: chemical conversion; photochemical reduction, including photocatalysis-based artificial photosynthesis; electrochemical and chemical reduction; biological conversion through autotrophic and heterotrophic pathways; methane reforming, in which methane reacts with CO₂ to

form synthesis gas; and inorganic conversion, such as direct air capture using alkaline absorbents including calcium hydroxide and potassium hydroxide [8]. Physical-process-based methods, including absorption, adsorption, chemical-looping combustion, membrane separation, hydrate separation, and cryogenic distillation, have been used to remove atmospheric CO₂. However, these methods can be expensive, inefficient, energy-intensive, and operationally complex, and may also create secondary environmental impacts [2,7,9]. One important reason for the high cost of CCS is that it does not necessarily convert CO₂ into higher-value chemicals. Carbon capture, utilization and storage (CCUS) therefore introduces CO₂ valorization by converting captured CO₂ into value-added products. Because CCUS combines emission reduction with the production of useful compounds, it may offer greater economic feasibility than CCS alone [1,7].

A key step in CCUS is CO₂ fixation, which requires an energy input, generally in the form of light, electricity, or heat. Different fixation routes have different energy requirements. Among the six categories described above, biological conversion uses biocatalysts, including enzymes and microorganisms, to perform reactions under relatively mild temperature and pressure conditions. Its energy demand is therefore generally lower, giving biological conversion potential economic advantages over many alternative approaches [1,8].

2. Biological Conversion Technologies

2.1. Autotrophic Microbial CO₂ Fixation

Microbial CO₂ fixation can be divided into autotrophic and heterotrophic routes. Autotrophic fixation mainly captures CO₂ through photosynthesis, with ribulose-1,5-bisphosphate carboxylase/oxygenase (RubisCO) serving as a key enzyme [7,8,10]. The most common photosynthetic cells in nature are plant cells and algal cells. Photosynthesis in plants requires substantial energy and materials to construct supporting, absorbing, and transporting structures and tissues, which reduces the fraction of energy available for carbon fixation. Algal cells, by contrast, do not need to build extensive

supporting structures because water provides physical support. They can therefore direct a larger share of available energy toward growth and reproduction, and their solar-energy-driven CO₂ fixation efficiency has been reported to be approximately ten times that of terrestrial plants [8,11]. Algae are consequently regarded as a favorable biological platform for photobioreactor development.

Photobioreactors require uniform light distribution and an adequate CO₂ supply. The cultivation environment must be controlled, the appropriate light wavelengths must be delivered to the culture, and sufficient gas-liquid contact area must be provided for CO₂ transfer. A typical configuration is the raceway-type photobioreactor. It has been estimated that fixing the CO₂ emitted by a 150-MW thermal power plant using such a system would require a reactor area of approximately 1.5 km² [8]. To reduce the land-area requirement, researchers have attempted to integrate absorption processes with microalgal cultivation [6]. Absorption is among the most mature CO₂ capture technologies and has been commercially applied in several countries. After absorption, CO₂ is generally present in the solvent as carbonate or bicarbonate. Because algal cells lack the specialized structures that higher plants use to transport gaseous CO₂ directly into cells, carbonate and bicarbonate in solution can serve as important direct carbon sources. The absorption-microalgae hybrid route is therefore favorable for algal CO₂ fixation [7-9].

2.2. Heterotrophic Microbial CO₂ Fixation

The Calvin-Benson-Bassham (CBB) cycle is the most common natural carbon-fixation pathway in autotrophic microorganisms. Its key enzyme, RubisCO, does not completely discriminate between oxygen and CO₂, resulting in limited catalytic efficiency [12]. To improve the carbon-fixation performance of algal photobioreactors, direct approaches such as RubisCO overexpression have been investigated, together with indirect approaches including the development of more efficient energy-harvesting systems and regulation of carbon-flux distribution [13]. These measures have not fully resolved the fundamental limitations of autotrophic systems, leading to increased interest in heterotrophic microorganisms as carbon-fixation hosts [12,13].

Heterotrophic microorganisms can produce chemicals such as lactic acid and acetic acid at relatively high productivity, and more advanced genetic tools, including CRISPR, are available for their engineering. To make heterotrophic microorganisms suitable for carbon fixation, their native metabolism must be modified. One route is to introduce key enzymes from natural carbon-fixation pathways into a heterotrophic host. Another is to develop new non-natural pathways, potentially providing greater opportunities to improve fixation efficiency [14]. Several key enzymes have already been introduced or engineered for such systems, including phosphoenolpyruvate carboxylase and enoyl-CoA carboxylase/reductase [14,15].

2.3. Microbial Electrosynthesis

Natural carbon-fixation pathways generally use light, hydrogen, or sulfur as their energy source. The conversion efficiency of light energy in biological photosystems is typically below 3%. The utilization of hydrogen is limited by the rate of hydrogen uptake, while microorganisms capable of using sulfur as an energy source are comparatively

uncommon. One possible solution is to use electricity as the energy input for artificial carbon-fixation pathways, an approach known as microbial electrosynthesis (MES).

According to the mode of electron supply, MES can be divided into direct and indirect electron transfer. In direct electron transfer, microorganisms such as acetogens and methanogens obtain electrons directly from the cathode. A major limitation of this route is that the detailed transfer mechanism has not yet been fully clarified, and further research is required before reliable engineering application can be achieved. In indirect electron transfer, electron donors or mediators provide reducing equivalents to the microorganisms. Representative substances include hydrogen, formate, flavins, ferrous ions, and ammonia [11,14].

3. Current Status and Development Trends

The conversion of inorganic carbon into organic compounds that can be used as fuels, chemicals, and manufacturing materials is a potentially effective approach for mitigating the greenhouse effect while providing sustainable resources. Over approximately eight decades of biological carbon-fixation research, six natural pathways have been identified [14,16]. Rapid advances in genome, metagenome, and microbiome projects may facilitate the discovery of additional carbon-fixation enzymes and pathways. Nevertheless, the low efficiency of natural fixation systems and their limited amenability to genetic modification make them inadequate for many industrial requirements.

Researchers are therefore attempting to construct more efficient synthetic systems. In addition to engineering key enzymes, partial or complete carbon-fixation pathways can be introduced into heterotrophic chassis cells to improve microbial fixation efficiency. Different carboxylases have been combined to create new carbon-fixation pathways, including the MCG pathway and the CETCH cycle. These examples demonstrate that more efficient carbon-fixation routes can be rationally designed and constructed. Beyond conventional light and hydrogen inputs, electricity is also being investigated as an energy source for biological carbon capture [7,14].

However, improving carbon-fixation efficiency to meet industrial requirements still involves several core challenges. First, the low activity of key fixation enzymes limits the productivity of natural pathways. Genome, metagenome, and microbiome programs, together with associated omics analyses, are generating large datasets that may support the discovery of new and highly efficient carbon-fixation enzymes. Screening naturally efficient carboxylases or designing non-natural carboxylases de novo are possible approaches to this problem. Carbon-concentrating mechanisms can also be introduced to increase substrate concentration and enhance carbon flux through synthetic fixation pathways.

Second, natural carbon-fixation pathways often contain many reaction steps and exhibit relatively low overall efficiency. Continued development of synthetic biology may enable the discovery of previously unknown natural pathways and the design of shorter and more efficient synthetic pathways. Third, low energy-utilization efficiency significantly weakens the economic performance of biological fixation. Solar energy is inexpensive, but the light-utilization efficiency of existing systems is often too low to

provide sufficient energy for large-scale CO₂ conversion. Poor penetration of visible light through microbial cultures further restricts scale-up. Converting light into other energy carriers, such as electricity or hydrogen, for direct carbon fixation may therefore be a promising direction. Expanding the range of wavelengths that can be biologically utilized may also improve overall light-use efficiency.

4. Conclusion

Biological CO₂ capture and utilization offers a route for linking greenhouse-gas mitigation with the production of fuels, chemicals, and materials. Autotrophic systems can directly use solar energy but remain constrained by RubisCO performance, light-transfer efficiency, and the large area required by photobioreactors. Heterotrophic systems and microbial electrosynthesis provide more controllable platforms and broader genetic-engineering options, but they depend on reliable synthetic pathways, efficient electron transfer, and scalable reactor integration. Future progress will require the discovery or design of high-activity carbon-fixation enzymes, construction of shorter synthetic pathways, improved carbon-concentrating mechanisms, higher energy-conversion efficiency, and closer integration between biological systems and industrial capture processes. Advances in these areas will determine whether microbial carbon fixation can achieve the productivity, stability, and economic viability required for large-scale industrial deployment.

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