Microalgae Organisms in Capturing Carbon Dioxide: Mechanism and Application

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Abstract. In recent years, the application of fixing carbon dioxide (CO_2) by using microalgae to reduce greenhouse effects has been considered a promising technology. Most researchers have paid attention to the economic value of this technology in the conversion of CO_2 into energy and fuel products without pollution. This article provides the latest progress on the principles and practical applications of microalgae in CO_2 capture, including biological products and biofuel products, and also discusses the challenges and solutions faced by microalgae technology and future expectation, which indicate that cynobacteria can help people alleviate energy crises and reduce the environmental issues of global warming by using natural biological animals to ease the pressure on the planet in an environmentally-friendly way. Based on the above introduction of the principles of microalgae technology, the article predicts the development prospects and potential of microalgae technology and proposes methods for the commercialization of microalga.

Keywords: microalgae, cynobacteria, carbon capture.

1. Introduction

During the perennial testing of greenhouse gases, scientists found that carbon dioxide (CO_2) was considered the most affectable greenhouse gas responsible for global warming, which moves through the carbon cycle naturally as it traverses from the atmosphere and returns after animal and plant death or combustion on Earth. This carbon cycle maintains a balanced concentration of carbon on the Earth. However, the reliance of humans on burning fossil fuels to get a source of energy causes substantial amounts of CO_2 to be released through artificial processing back into the natural atmosphere, disrupting the natural balance within the carbon cycle while producing excessive greenhouse gases that contribute to lead climate change [1]. The increased concentration not only affects the global temperature but also reduces the ability of animals to transfer oxygen and causes biodiversity issues [2], the Earth's sea level will rapidly rise, and freshwater resources will be replaced by the ocean. According to NASA, the present temperature change on Earth indicates that while Earth's climate has changed its history, the ongoing rate of warming is unusually rapid [3]. The annual report from NOAA's Global Monitoring Lab shows that the average global CO_2 concentration reached 424 parts per million(ppm) in May 2023 which is a new record high number in the past years, and from 1960 to 2023, the amount of CO_2 increases almost 50 ppm. The environment management predicted that the concentration of CO_2 will rise to 550ppm by 2050 which will be a serious environmental problem for the planet [4]. Afterward, a series of measures have been taken to address the problem of increased greenhouse gas emissions on the planet. Carbon capture and storage (CCS) technology is a form of carbon sequestration aimed at contributing to achieving net zero by 2050.

In the area of carbon dioxide capture, current techniques involve converting CO_2 into solid minerals through carbon mineralization and storing carbon dioxide as $CaCO_3$ on Earth's surface. However, this technology faced the drawback of the natural processes for carbon mineralization are slow and take at least two years. To overcome this limitation, humans have developed accelerated methods, on the other hand, these require significant financial resources. Additionally, standalone CO_2 capture involves large-scale machinery and equipment that consume substantial energy and require human labor input. Faced with challenges posed by artificial technologies reliant on energy sources, humans are now exploring potential collaborations with animals and plants to efficiently process the level of atmospheric CO_2 thereby mitigating greenhouse effects effectively [5]. Through research, it has

revealed that algae possess a vital role in Earth's photosynthesis. Cyanobacteria was considered as the fastest rate of growth of algae due to a wide range of antenna pigments even though they have particularly surged and caused flooding in certain regions. Consequently, scientists are now exploring the ability of CO_2 photosynthesis aid to in reducing climate change [6].

Microalgae are considered one of the most effective methods of carbon fixation in the world. Microalgae technology utilizes natural substances like cynobacteria to minimize the adverse effects of CO_2 on Earth's greenhouse effect. Moreover, microalgae technology does not produce any additional harmful substances or push pressure on Earth's energy consumption requirements. Hence, it serves as a sustainable and naturally occurring method facilitating environmental equilibrium. As shown in Fig. 1, the cynobacteria bio composite can combine with synthetic biology tools to produce carbon capture systems, this technology not only promotes environmental friendliness but also demonstrates economic feasibility and long-term sustainability [7]. The ability of microalgae to fix carbon dioxide through photosynthesis is 10-50 times that of other terrestrial plants [8]. They exhibit a superior ability to recover CO_2 into bioenergy through photosynthesis and can convert smoke from power plants and other industrial waste gases into inorganic carbon sources [9]. Additionally, they showcase adaptability towards various environments, microalgae cultivation does not depend on fertile land and thus avoids any competition with human food resources, and can be planted on nonarable and marginal land [10]. Cyanobacteria utilize photosynthesis to transform CO_2 into organic substances. They typically thrive at high CO_2 levels making them appealing to contemporary industries that aim at finding efficient approaches for capturing CO_2 from flue gas emissions [11]. Common cynobacteria used in the industry such as Chlorella, Scenedesmus, Chaetophora, and Navicula, these cynobacteria are algae that can use for catching CO_2 in wastewater treatment. These methods exhibit an extremely strong ability to absorb CO_2 and are considered an environmentally friendly way to absorb wastes in wastewater [12].

The purpose of writing this review is to investigate the potential of a carbon capture program mediated by microalgae organisms, including technical principles, current situations, challenges, and technology prospects.

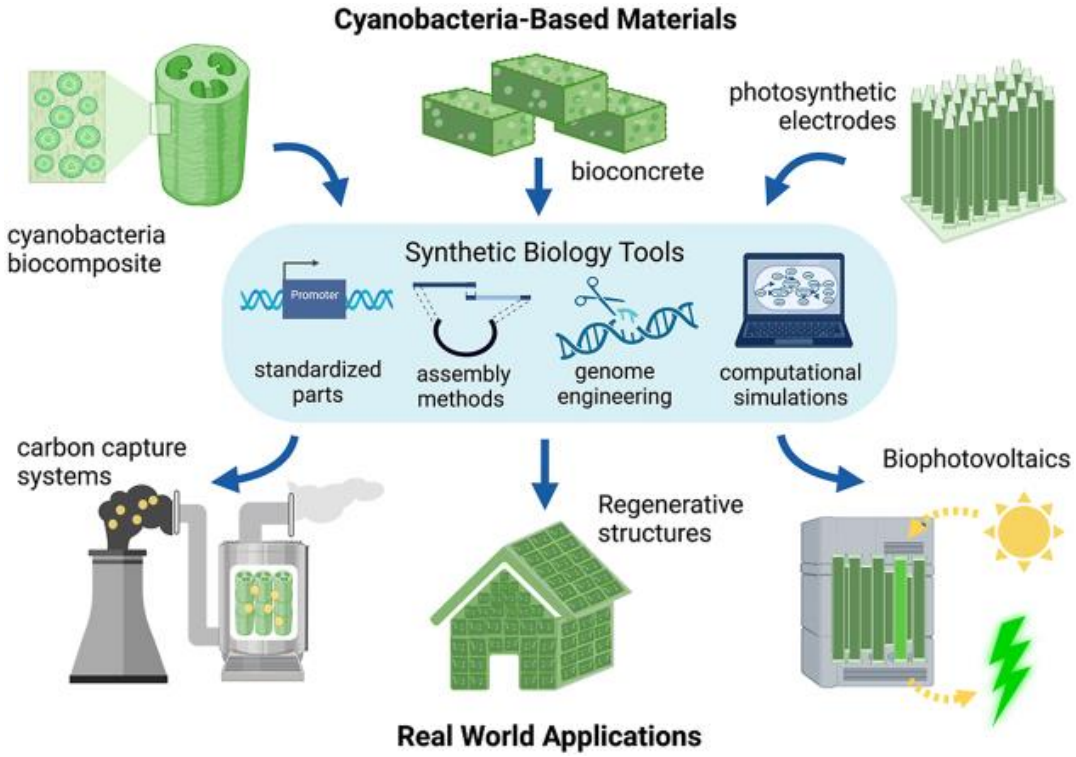


Figure 1. Process of using Cynobacteria to capture CO_2 [7].

2. Microalgae Technology for CO_2 Capture

Cyanobacteria of blue algae are a group of gram-negative bacteria, they carry out oxygenic photosynthesis and can be found in various environments worldwide. They widely survived in aquatic habitats like oceans, lakes, rivers, etc., as well as in terrestrial habitats such as moist soils. Additionally, they are considered resilient organisms that can survive even under extreme regions such as deserts or areas with permafrost formations [11]. Moreover, cyanobacteria may exist either singularly or form complex structures resembling filaments or spheres alongside other cyanobacteria, their existence plays a crucial role in generating oxygen essential for sustaining life on Earth [13]. Their survival greatly regulates the changes in the world's climate change and helps alleviate the greenhouse effect.

Cyanobacteria account for more than 50% of the world's carbon fixation [6]. In ancient times, cyanobacteria played a crucial role in producing large deposition of carbon-rich sediments, which later became essential fossil fuels supporting organisms' survival. Contemporary cyanobacteria are responsible for oxygen production and providing food for organisms to sustain life on Earth [14].

To absorb CO_2 more efficiently, cyanobacteria have evolved a useful adaptation mechanism of the natural environment called the CO_2-concentrating mechanism (CCM). CCM is a metabolic system that enables the absorption of inorganic carbon and CO_2 fixation, as shown in Fig. 2 allowing bacterial cells to accumulate CO_2 located at the Rubisco site which is the simplest photosynthetic complex forms by subunit composition [15]. It greatly improved the degree of photosynthesis and the survival rate of cyanobacteria under controlled or finite CO_2 concentration [16]. The CCM operates to actively make transportation and accumulation of inorganic carbon within cyanobacteria cells, specifically utilizing the Ci pool to create higher concentrations of CO_2 near Rubisco [16].

CCM is composed of bicarbonate absorption transporters on the plasma membrane and NDH and carboxysomes on the thylakoid membrane. This system works by converting freely diffusing CO_2 into bicarbonate through the NDH enzyme. The resulting bicarbonate then enters the carboxysomes where it undergoes conversion back to CO_2 utilizing an enzyme called carbonic anhydrase. This newly-formed CO_2 serves as a substrate for rubisco and helps create a difference in CO_2 concentration between the inside and outside of cyanobacteria cells, making it easier for CO_2 gas molecules to diffuse into the cell membrane along the concentration difference [17]. Due to this mechanism, the concentration of inorganic carbon is much higher than 200-300 μM and saturate the required CO_2 concentration for the working of Rubisco. In addition, a high concentration of CO_2 increases the amount of the ratio between CO_2 and O_2, resulting in the degree of carboxylation exceeding oxygenation [18]. The rate of adding carboxyl functional groups to the substrate is higher, which causes the rate of conversion and absorption of carbon dioxide higher.

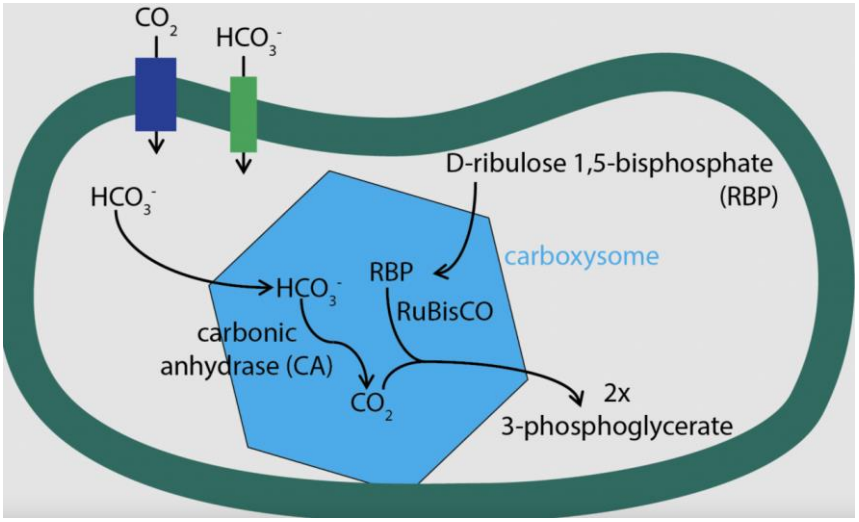


Figure 2. Mechanism of Cyanobacteria reacting with Rubisco inside the cell [19].

3. Application of Cyanobacteria in CO_2 Capture

Microalgae are microorganisms that thrive on photosynthesis and can utilize CO_2 from the atmosphere as the raw material for growing and producing biomass as a result. During this process, the medium containing microalgae can help to absorb CO_2 during photosynthesis and convert CO_2 into organic compounds [20]. By following the growth of microalgae, they absorb CO_2 gas and sequester them in bacterial cells. This method indicates the reduction of CO_2, on the other hand, it was also helpful for producing various biological products, such as biofuels [21].

3.1. CO_2 capture from wastewater

Firstly, the fabric-based prototype has been created to capture CO_2 by using cyanobacteria during the process of treating wastewater [7]. Cyanobacteria can help to capture CO2 in wastewater. Microalgae exhibit photoautotrophic behavior and can directly utilize dissolved elements of nitrogen (N), phosphorus (P), and organic carbon (OC) for growth. In wastewater treatment, it often requires many processors which is an advantage for microalgae has a large abundance of supply that can be found in both fresh water and seawater. Therefore, local cyanobacteria can be used for agriculture to prevent potential safety hazards, and the strategy of cultivating large-scale microalgae outdoors does not require a huge land area. Meanwhile, microalgae cultivation technology may be a single method for simultaneously achieving CO_2 capture and nutrient removal from wastewater, without generating secondary pollution [22].

Algae-based wastewater treatment methods help treat CO_2 in wastewater with a minimal CO_2 footprint. In the traditional process of water treatment, aeration is necessary to the exploiting of both organic and inorganic bacteria which need aerobic reactions for their growth. It typically has 400–500 mg COD L^{-1} change from 0.25 to 1.89 $kWhm^{-3}$. However, when cynobacteria process in the photosynthesis growth of cyanobacteria does not need mechanical aeration. It can save energy and does not produce sludge as environmentally friendly and sustainable technology [23]. Until now, the highest fixing rate of CO_2 from cyanobacteria is 1.496 g CO_2 L^{-1} wastewater, which maintains a high value for treating wastewater in a natural way [23].

Cyanobacteria are environmentally friendly in terms of energy substitution and CO_2 fixation, but their slow growth rate is an obstacle to industrial application. These cyanobacterial chassis lack the necessary and strong tolerance to toxic products or chemicals such as fuels. This becomes a problem when attempting industrial production, as many products like bioethanol and lactic acid are harmful to the growth of cyanobacteria which will affect their growth rate. Additionally, wild-cultivated cyanobacteria frequently face contamination from chemical factors. The inadequate productivity of these cyanobacterial chassis results in difficulties during product harvesting at low concentrations that require a decrease in their growth rate [24]. Otherwise, the growth rate in Fig. 3, there are some general industrial areas using cynobacteria, these industries cause a great supply of using cyanobacteria and can probably face challenges as the growth rate.

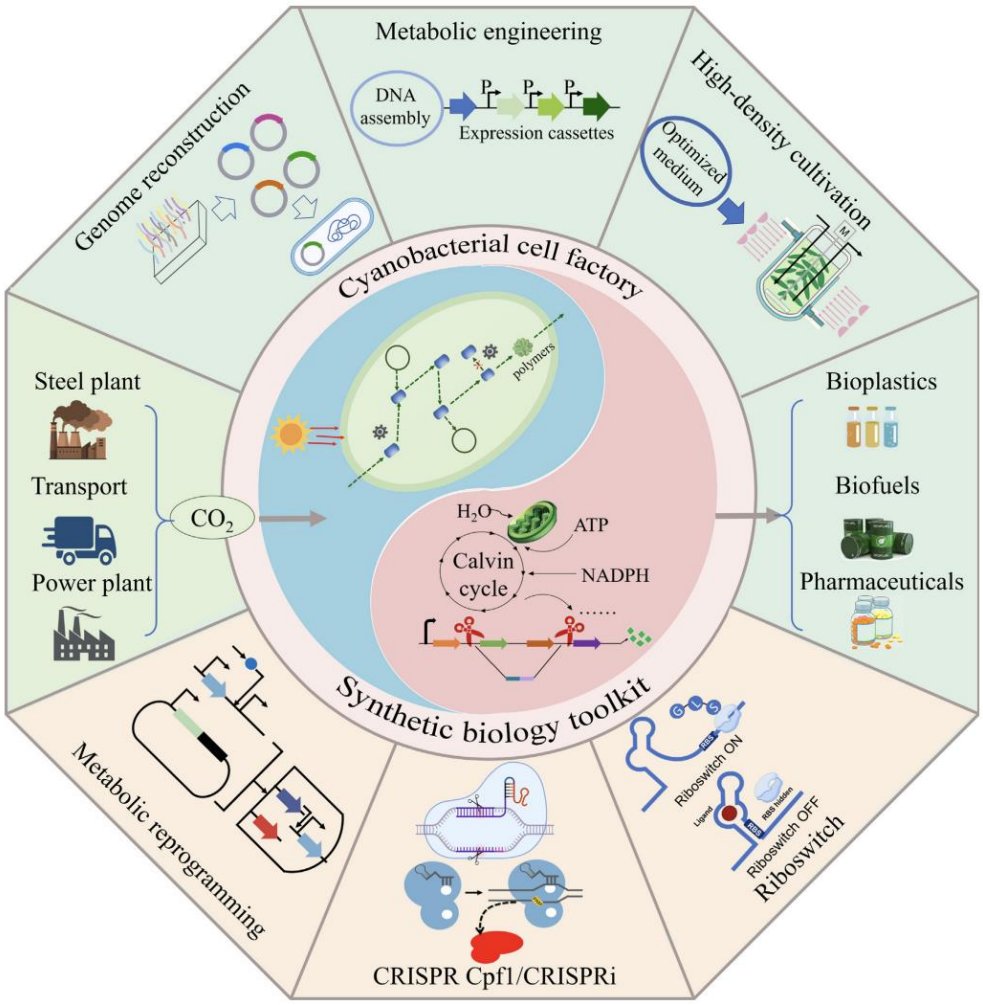


Figure 3. Common industrial areas using Cynobacteria [10].

3.2. Bioproducts formed by CO_2

After they capture CO_2, Cyanobacteria have been modified to serve as eco-friendly platforms for generating fuels and value-added chemicals. Synchronous elongatus 7942 and Synechocystis sp. 6803 the most researched cyanobacteria, have been extensively researched for their ability to perform oxygenic photosynthesis and act as natural photoautotrophs. These two substances are created to make bioproducts collectively. Their notable attributes include high-energy densities, compatibility with contemporary fuel processing plants, and applicability in the food industry. Among various chemicals investigated for production in cyanobacterial strains, alcohols stand out due to their prominence. Ethanol has exhibited impressive results including substantial yield improvements within Synechocystis 6803 cells when produced at high concentrations.

By integrating the biosynthetic platforms, Elongatus 7942 and Synechocystis 6803 have effectively generated widely utilized industrial substrates like is butyraldehyde, lactic acid, and 3-hydroxypropionic acid. Lactic acid was widely used in the area of food industries, pharmaceutical production, and polymer trades. Furthermore, by optimizing Synechocystis 6803, enhanced effectiveness has been achieved in lactic acid production. Additionally, the optimization of elongatus 7942 has led to enhanced productivity in producing vital chemicals such as 2-3 butanediol (23BD), an essential component for producing elastomers and polyurethane items. Although the new production achievements employed for 23BD production in S. elongatus 7942 exhibited promising results, the quantities produced remained insufficient to be economically viable or competitive compared to existing petroleum-based alternatives [25].

3.3. Biofuels

There have been advancements by material scientists in the development of biomaterials that are based on cyanobacteria. These materials have various applications such as carbon capture, building construction, and new types of energy generation. Most of these biomaterials are used as engineering living materials (ELMs). In terms of technology, many projects utilize living microalgae to develop and design new intelligent technologies. To create regenerative building material, researchers have taken advantage of the natural biomineralization process of cyanobacteria. They combine a stand with hydrogel-sand with Synechococcus elongatus PCC 7002 resulting in a scaffolding made from renewable resources. The materials produced by cynobacteria are naturally no pollution, and their biofuels can offset greenhouse gas emissions through additional plant growth [26].

3.4. CO_2 capture from atmosphere

The technology of using cynobacteria as a biological method for CO_2 adsorption is considered promising and the development of the technology is ongoing following the deeper exploration of types of cynobacteria. By facing these growing rate problems, scientists explored a lot of methods to help solve this problem. Scientists have discovered the fastest-growing cyanobacteria strain, Synechococcus elongatus UTEX 2973, and Synechococcus sp. PCC 11901, which has high biomass production under low light intensity increases the growth efficiency of cyanobacteria. Scientists have found that all strains growing under atmospheric CO_2 conditions and low light intensity exhibit similar multiple times. Under high-intensity lighting conditions, the UTEX 2973 strain growth increased in atmospheric CO_2, but it was probably due to other issues. The data shows that the optimal growth conditions for PCC 11901 are 38 ^oC, 1% (v/v) CO_2, at 660 μ. In summary, the biomass accumulated by all strains under high light irradiation has slightly decreased which influences the growth rate [27].

4. Technology Prospects

To improve microalgae technology, scientists have studied how to solve the problems faced by microalgae during CO_2 treatment, which can enhance the efficiency of microalgae in adsorbing CO_2 and solving global warming issues.

4.1. Extension

Scientists predict that this adaptive evolution strategy of increasing the efficiency of algae can also be used to artificially domesticate the cyanobacteria chassis of super cyanobacteria, allowing cyanobacteria to be tolerated under high light intensity and high concentration of salt photosynthesis efficiency, thereby accelerating commercialization.

4.2. Biofilm Attachment

Cultivating microalgae on a large scale and providing them with the necessary nutrients is expensive. To improve the algae growth rate that was mentioned earlier, however, scientists have discovered an innovative technique called biofilm attachment to culture algae more efficiently. They have also found that using various sources such as industrial waste, agricultural runoff, and sewage sources for microalgal production holds great potential in reducing ecological impact significantly [28].

4.3. Microalgae Cultivation on Anaerobic Digestate

Additionally, biogas residue along with nutrient-rich wastewater from both biogas plants and anaerobic digesters are incorporated into microalgal cultivation systems to further enhance growth by supplying concentrated nutrients like ammonia, potassium, phosphorus, sulfur, and resilient organic substances primarily consisting of nitrogen elements [29].

4.4. Large Scale Production

On the other hand, a more common and mature technology for scaling algae is tubular photobiological reactors with an open raceway system, and flat panel systems, which are suitable for outdoor scale microalgal production. These ways can highly control the degree of enhancing the growth of algae thus reducing operational costs [30].

5. Summary

Microalgae technology has played an important and effective role in the capture and utilization of CO_2, which can help the planet reduce climate change and greenhouse effect issues, and also microalgae technology can replace CO_2 products with more useful and eco-friendly materials, in the development of this field, many technologies have strong potential. In this paper, the principle of CO_2 absorption by rapid photosynthesis of Rubisco and the mechanism of CO_2 concentration through the complex internal structure of algae were introduced, as well as the benefits of CO_2 conversion into products or algae into fuel after practical application on algae to release pressure on the environment. The article also summarized some discoveries and mature technology to reveal the possibility of improving the microalgae technology, such as biofilm attachment and microalgae cultivation which can make higher productive efficiency of microalgae. Last but not least, microalgae technology not only has significant effects in capturing and utilizing carbon dioxide but also relieves humans from resource pressure and makes efforts in the development of many products and energy substitution, the development of this technology is considerable.

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