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Bio-mitigation of carbon dioxide using microalgal systems: Advances and perspectives

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ABSTRACT

Carbon sequestration is an important strategy in combating rising carbon dioxide concentration in the atmosphere. Differing from carbon emission reduction, carbon sequestration offers the possibilities of reducing or avoiding CO_2 emission if CO_2 is to be captured from large stationary sources and utilization of the captured CO_2 for production of chemical and energy. Biological sequestration or bio-mitigation of carbons through microalgal systems, despite in its early stage, represents a promising and sustainable alternative to current carbon mitigation methods. Microalgae consist of a group of highly diverse and fast-growing microorganisms, capable of photoautotrophy, heterotrophy, and mixotrophy. They can be cultivated on non-fertile land with unit CO_2 fixation capacity 10–50 times higher than terrestrial plants. Production of food, feed, fine chemicals, and biofuels from microalgal biomass could further enhance the benefits of microalgae-based CO_2 fixation. This present review is aimed to gain understanding how microalgae assimilate different forms of carbons and provide a comprehensive overview of the current advances in utilizing microalgae for CO_2 fixation, with focus on strain screening and improvement, mass cultivation practice, and effects of environmental and nutritional factors on CO_2 fixation performance. Economic viability, challenges and perspectives of microalgae-mediated CO_2 bio-mitigation are also discussed.

1. Introduction

CO_2 represents 68% of greenhouse gases (GHGs) emission into the atmosphere [1] and is a major contributor to the global warming. The Kyoto Protocol and the Paris Agreement set ambitious goals and responsibility for participating countries to curb GHGs emission. While these agreements are to limit CO_2 emission, there is another aspect in the reduction of CO_2 in the atmosphere, i.e., CO_2 sequestration [2–4]. The technical benefits of CO_2 sequestration are three folds: first, it reduces CO_2 concentration in the atmosphere; second, it reduces or avoids CO_2 emission if CO_2 is to be captured from large stationary sources [5,6]; third, the captured CO_2 can be used as a feedstock or substrate for production of chemical and energy products [5,6]. In addition to these technical benefits, CO_2 sequestration and utilization can generate new economic and job opportunities.

There are many techniques for CO_2 sequestration, which may be classified into the physical, chemical, and biological categories. Each of them has advantages and disadvantages. The focus of this review is biological platform, specifically, microalgae-based approach. [5,6] (Detailed in Table 1). Physical storage refers to the processes that directly inject highly concentrated CO_2 into deep ocean, aquifers or depleted oil/gas wells [7]. By contrast, chemical fixation involves CO_2 immobilization using adsorption material (such as lithium hydroxide) followed by alkaline-mediated neutralization leading to the formation of carbonates or bicarbonates. Both have their own advantages and shortcomings [7]. Physical methods such as direct CO_2 injection are

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Table 1
Comparison of various CO_2 sequestration methods [123–131].

Category	Method	Mechanisms	Prospects	Limitations
Physical	Membrane separation	Isolation of CO_2 from the main stream by passing mixed gas through a membrane	1) increased mass transfer	1) energy inefficient 2) membrane fouling and blockage 3) high cost
	Geologic injection	Injection of CO_2 into geologic reservoirs, depleted oil/gas wells, and coal seams	1) make use of abandoned space 2) relative easy operation 3) possible recovery of oil/methane	1) requirement of particular geological and geomorphological environment 2) gas leakage over time (several thousand years) 3) high cost
	Oceanic injection	Injection of CO_2 into deep ocean	1) large CO_2 holding capacity	1) gas leakage over time (several hundred years) 2) threaten the lives of non-swimming marine organisms 3) requirement of high-cost injection techniques
	Adsorption	Using molecular sieves or zeolites	1) minimal waste generation 2) flexible to different CO_2 sequestration schemes	1) energy inefficient 2) co-adsorption of other components (SO_X)
Chemical	Chemical absorption	Neutralization of carbonic acid to form carbonates or bicarbonates	1) safeandpermanent sequestration 2) rich supply of required base ions (Na^+, K^+)	1) large equipment size requirement 2) high energy requirements 3) high cost
	Mineral carbonation	Reaction of CO_2 with metal oxides to form stable carbonates	1) abundantly available metal oxides (MgO, CaO) 2) safeandpermanent sequestration 3) utilization of stable carbonates after sequestration	1) requirement of large amount of reagent 2) not cost-effective
Biological	Forestation	Incorporating atmospheric CO_2 into biomass over the lifetime of trees	1) chemical-free	1) limited CO_2 sequestration 2) large land area requirement 3) potential threat to biological diversity and food supply
	Oceanic fertilization	Triggered growth of photosynthetic organisms by extra iron sources	1) significant increase in CO_2 sequestration	1) high cost 2) high level of uncertainty 3) impact on ocean eco-system (change in plankton structures) 4) possible trigger of methane production
	Microalgae-based sequestration	Utilization of CO_2 via microalgal photosynthesis	1) high photosynthetic efficiency 2) efficient in low-concentration CO_2 sequestration 3) faster sequestration rate than higher plants 4) do not compete with crops for arable land 5) co-production of food, feed, fuel, fine chemicals, etc.	1) sensitive to toxic substances in exhaust gases 2) not very cost-effective for photobioreactors construction and algal biomass harvesting

suitable for large-scale CO_2 sequestration; however, they require certain geological and geomorphological structures, expensive separation equipment and technologies to collect and concentrate CO_2, uncertainties, and risk with long term leakage, etc. [7]. Chemical neutralization methods are a relatively safe and long-term CO_2 fixation process but not cost-effective, as large amounts of reagents are necessary for neutralization [7]. Furthermore, both physical and chemical methods are faced with challenges in capturing CO_2 from low concentration and diffused- or non-point sources [8,9].

This review is intended to demonstrate the potential of microalgae based approach to tackle these challenges. Carbon is the main component of microalgae cells, accounting for about 50% of cell dry weight. It is estimated that 100 tons of microalgal biomass production is equal to around 183 tons of CO_2 fixation [4,10]. Microalgae have the ability to sequester low concentration CO_2 from air or high concentration CO_2 from stationary sources such as coal burning power plants, and inorganic and organic carbons in wastewater. Furthermore, algae can effectively utilize N and S containing pollutants, suggesting a potential of reducing NOx and SOx, potent GHGs. [5,11].

Microalgae are photosynthetic cell factories that possess many unique characteristics well suited for CO_2 sequestration. Microalgae are able to use natural sunlight as energy for CO_2 fixation with high photosynthetic efficiency that is 10–50 times higher than terrestrial plants [12]. They can tolerate extreme environments such as saline-alkali land, desert, and beaches without competing with crops for arable land [10,13]. They grow much faster than higher plants with doubling time within 2–4 h [14]. They can feed on flue gas from power plants as inorganic carbon source and wastewaters from municipal, industrial and agricultural activities as nutrient source (N, P) [3,15–20]. Microalgae can serve as carbon neutral single-cell bio-factories for the production of food, animal and aquaculture feed products, cosmetics, nutraceuticals, pharmaceuticals, fertilizers, bioactive substances, and biofuels [4,11]. Moreover, microalgae have been used in indoor air purification, exhaust gas treatment from automobile, power plants and other industries and have the potential for CO_2 removal and O_2 generation for life protection system control in confined spaces such as nuclear submarines and manned spacecrafts [21].

Carbons may emit to the atmosphere from natural and human sources such as decomposition of organic materials, respiration of living organisms, and burning/combustion of plant and fossil fuels during manufacturing and agricultural activities, transportation, and other human activities. Carbons may be in the form of atmospheric CO_2 (0.03–0.06%, v/v), soluble inorganic carbonate (HCO_3– and CO_3^{2-}) and organic carbons (simple sugars and short fatty acids) [4,12,21]. Fig. 1 schematically illustrates a concept of integrating microalgae-based carbon sequestration with utilization of the captured carbons. In this concept, nitrogen (N) and phosphorus (P) rich wastewaters replace the artificial media to support microalgae growth, nutrients and CO_2 are recycled during downstream refining processes, and the harvested algal biomass is converted to renewable bioproducts and bioenergy. The realization of the concept is expected to enhance the economic viability and environmental friendliness of microalgae-based CO_2 fixation systems.