Journal of Bioremediation & Biodegradation

Chawla et al., J Bioremed Biodeg 2014, 5:5
http://dx.doi.org/10.4172/2155-6199.1000234

Research Article Open Access

# Photobioreactor for $CO_2$ Sequestration: Possibilities and Challenges

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**Rec date:** May 19, 2014, **Acc date:** Jul 14, 2014, **Pub date:** Jul 18, 2014



## Abstract

Global warming due to increased $CO_2$ emission has become a major issue today. In this regard, algae offer a plethora of opportunities due to its photosynthetic route of conversion of $CO_2$ to biomass which is manifold higher than that of plants. In this regard, this paper highlights the issues, challenges and opportunities generated through algal sequestration of $CO_2$. The paper talks about various factors that enhance the efficiency of algal consumption as well as accumulation of $CO_2$. The parameters like mode of cultivation, photobioreactors design considerations and harvesting of algal biomass have been given due importance. The perspectives offered will provide a deep insight into development of an integrated technology for making $CO_2$ sequestration commercially viable.

**Keywords:** Photobioreactor; Carbon dioxide; Sequestration; Algae; Global warming; Climate change

## Introduction

Increased energy and water demand has resulted in degradation of the environment. Current energy demands are mostly met by conventional sources often leading to emission of greenhouse gases [1]. Across the globe, from developed economies to developing ones, there is a lot of interest generated in finding sustainable solutions to increased $CO_2$ emissions. Algal mediated wastewater treatment and $CO_2$ sequestration could provide impetus to counter concern for clean water, air and energy, effectively treating even complex contaminants like heavy metals and polycyclic aromatic compounds [2-4]. Moreover, algae that have high rate of $CO_2$ sequestration are now preferred for biodiesel production due to their high rate of lipid/oil accumulation going as high as 58,700 L oil per hectare [5,6].

Several models have indicated the techno-economic feasibility of integrated algal use by utilizing nutrients from wastewater, carbon from waste gases and subsequent production of biofuel [7]. The key problem associated with the current research is that the investigations are mostly confined to laboratory experiments where often the conditions are controlled which deviate a lot from the real ones. On a larger scale, the applicability of lab findings itself become a challenge. In some cases, the size has been increased to a mere pilot scale of 1000 L but owing to difficulties in scale up of the given design, less breakthroughs have been achieved in design of bioreactor where scale up is taken to industrial level in case of simultaneous $CO_2$ sequestration and waste water treatment [8].

## Strain selection and mode of cultivation

There are multiple parameters to be taken care of for algal mediated $CO_2$ sequestration. The very basic and primary step is strain selection. Certain desirable qualities include tolerance to high $CO_2$ concentration, high biomass productivity, tolerance to variations in temperature and most importantly high $CO_2$ fixation rates. Most commonly used algal species are depicted in Table 1.

Strain selection is directly linked with mode of cultivation. The conditions of cultivation of algae have a peculiar effect on end result. The photoautotrophic cultivation mode utilizes light for energy requirement and inorganic carbon as carbon source. In this mode, there are large variations in lipid content which can be tilted towards user's advantage by increasing the lipid accumulation through nitrogen limiting condition [5,9]. Totally opposite mode of cultivation is heterotrophic condition where algae utilize organics for both energy as well as nutrient requirement. Since it does not require light, hence it is under the dark conditions [10,11]. Another mode of cultivation is the mixotrophic growth where light is used an energy source and depending upon the availability, both organics as well as inorganics are used as nutrient source. This is particularly required in cases where algal cultures are cultivated in wastewater with $CO_2$ injection. In such cases, algae utilizes light for energy, $CO_2$ as carbon source while simultaneously utilizing organics for treatment of wastewater hereby making the process more economically viable [7,12,13].

| Reactor type | Algal cultures | Inlet CO2 (%) | CO2 Fixation / utilization efficiency | References |
|---|---|---|---|---|
| Three-stage serial tubular Photobioreactor | *Spirulina* sp. | 6% (v/v) and 12% (v/v) | 53.29% and 5.61% respectively | [14] |

| | | | | |
|---|---|---|---|---|
| Membrane Photobioreactor | *Chlorella vulgaris* | 1% (v/v) (3 L/min) | 80 to 260 mg l –h-1 | [15] |
| Vertical tank Photobioreactor | *Chlorella* sp. | 2%, 5%, 10% and 15%, at 0.25 vvm | 0.261, 0.316, 0.466 and 0.573 g h-1 | [16] |
| Outdoor open Photobioreactor | *Chlorella* sp. | Flue gas (6–8% v/v CO2) | 10-50 % | [17] |
| Membrane Carbonation Photobioreactor (bubble-less) | *Synechocystis* sp. PCC6803 | 29 g C/m3 | 88% | [18] |
| Tubular Photobioreactor | *Chlamydomonas* sp. | 10%-40% (Variable flow) | 3-12% respectively | [19] |
| Air lift Photobioreactor | *Scenedesmus obliquus* | Flue gas (18% CO2) | 67% | [20] |
| Internally illuminated Photobioreactor | *Nannochloropsis salina* | 0.035-2% | 0.57-2.35 g CO2 1-1 d-1 | [21] |

**Table 1:** Performance of various algal cultures and photobioreactors with respect to CO2 fixation

## Photobioreactor design considerations

Once the strain selection is made, well designed photobioreactor becomes need of the hour. Cultivation could be done in open as well as closed system. Open systems, like unstirred ponds, circular ponds, raceways and modified raceways offer ease of operation and are more economical than closed system [22]. Major constraints offered by open systems include poor light utilization efficiency, huge evaporative losses and biological contamination. For high rate of $CO_2$ sequestration, open system are not viable as gas mixing becomes a challenge due to low depth of ponds [23]. When the efficacy of algal mediated $CO_2$ sequestration was tested in outdoor open photobioreactor, the results indicated that flue gas decarbonisation decreased with increasing flue gas injection rate into culture [17].

For high rate of $CO_2$ sequestration, mainly closed type photobioreactors are employed. The various design parameters for closed type photobioreactors include type of reactors, height to diameter ratio, mode of delivery, minimizations in temperature variations, optimum intensity of light, maximum utilization of light, proper mixing, optimum light - dark cycles, minimization of $CO_2$ losses. As depicted in Table 1, multiple designs of photobioreactors present multiple opportunities and challenges. These include mainly tubular type photobioreactors (horizontal and vertical), stirred tank photobioreactors and flat panel photobioreactors. Tubular photobioreactors are fairly easy to operate with decent biomass productivities due to high illumination surface area [22]. This system incorporates gas sparging as a means to provide overall mixing and high gas transfer efficiency [24]. Other variants include bubble column photobioreactor and airlift photobioreactor [25]. In a three stage tubular reactor, though the $CO_2$ fixation rate was high yet the problems associated with flocculating *Spirulina* sp. highlighted the importance of strain selection [14]. In the study concerning vertical tank reactors, it was noted that the algal sequestration of $CO_2$ could be increased by multiplicity of reactors hereby presenting an insight with regard to scale up [16]. In case of membrane photobioreactor, gas ($CO_2$) exchange efficiency improved from the introduction of membrane module hereby resulting in minimization of losses [15]. While in membrane carbonation photobioreactor the bubble less gas transfer through membranes allows precise control of $CO_2$ delivery hereby minimizing the loss of $CO_2$ to atmosphere [18]. There is also need to highlight the maximized fixation of $CO_2$ by optimizing the light intensity for minimization of $CO_2$ losses [20].

Light intensity can also be increased by better designs (internally illuminated) where light utilization rate is significantly higher as compared to bubble column and airlift reactors [21]. Studies have exhibited equal importance of dark cycles for algal growth. The dark cycle allows for re-oxidation of electron transporters of photosynthetic apparatus for sustained productivities [26]. Even the importance of optimum concentration where one has to remove the excess biomass continuously in order to provide maximum spread area to volume ratios, can't be ignored [27].

## Harvesting of algal biomass post $CO_2$ sequestration

Keeping in mind the process economics, significant economical addition to the entire process can be done through harvesting of algal biomass and then use of algal biomass for bioenergy generation [7]. Depending upon the scale, size and density of algal culture, various harvesting techniques like centrifugation, flocculation, gravity sedimentation, filtration, electrophoresis etc. can be employed. Centrifugation can result in high harvesting efficiency but the process is costly and energy intensive [28]. Flocculation is a process where particles form heavy aggregates which make their settling easily [29]. This could be done via increase in pH (autoflocculation) through base (NaOH) addition or through chemical flocculants like ferric chloride ($FeCl_3$) or aluminium sulphate $Al_2(SO_4)_3$ [24]. Success of gravity sedimentation highly depends upon size and density of algal cultures [30]. Efficiency of gravity sedimentation can be increased using flocculation [29]. Filtration involves passing of culture through screen of particular pore size. Major associated problem with filtration is high concentration of algal biomass often results in blocking of filtering material [31]. Other techniques include electrophoresis where electric current induced electrostatic field forces the movement of charged algal cells out of solution [32].

## Recent large scale developments in the field of $CO_2$ sequestration

The ENN group from China has developed a technology where a microalga is used to fix $CO_2$ released from coal production and subsequently biofuel is produced. The pilot plant consists of equipment required for microalgae cultivation with $CO_2$ absorption, oil extraction and bio-diesel production. This pilot system can absorb 110 tonnes of $CO_2$ and produce 20 and 5 tonnes of bio-diesel and proteins per year, respectively. Based on this pilot plant, a demonstration project has been initiated by ENN group in Dalate

(Mongolia) in 2010 where microalgae will be utilized to absorb $CO_2$ emitted from flue gas of coal-derived methanol and coal derived dimethylether production equipment and will produce biodiesel and feed.

Another group from Sweden, has set up a pilot plant in eastern Germany where algae is used to absorb greenhouse gas emissions from a coal-fired power plant. The gas emitted from the brown-coal-fired plant is pumped through a broth into the plastic tanks where algae is cultivated. The resultant algal biomass is used to produce biodiesel, to feed biogas power plants and as a nutrient supplement for fishes.

## Conclusion

There is a need for informed and effective design of photobioreactor which could replicate the real conditions and could provide an alternative solution. In this cost driven world, this idea of algal use is bound by importance of light as a parameter in algal growth. Across the world, there are places with abundance of sunlight available almost throughout the year. This advantage is still underutilized mainly because of lack of bioreactors which maximizes algal productivity and $CO_2$ sequestration. While the $CO_2$ sequestration offers huge environmental benefit, one has to make effort in the direction to make it economically viable. This can be made possible by integration of $CO_2$ sequestration with wastewater treatment and biofuel generation.

## Acknowledgement

Authors are grateful to Ministry of New and renewable Energy, Government of India for financial support.

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