ChemTech

International Journal of ChemTech Research
CODEN(USA): IJCRGG ISSN : 0974-4290
Vol.4, No.4, pp 1746-1753, Oct-Dec 2012

Techno Economic Analysis Of Micro Algal Carbon Sequestration And Oil Production

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Abstract: The global concerns of increasing atmospheric concentration of green house gas emissions and world energy demand has led to the substantial interest in developing sustainable energy sources. The greenhouse gas most commonly produced by burning fossil fuels is carbon dioxide (CO_2), which is responsible for 63% of global warming. Micro algae are viewed as sustainable approach for Carbon fixation. Microalgae are capable of fixing CO_2 using sunlight to produce biofuel and other chemical compounds with numerous additional technological advantages. This present study highlights the concept of algal carbon sequestration and biofuel production using open raceway ponds and closed photo bioreactor. This article addresses its technical and economic aspects.
Keywords- Micro algae; Photosynthesis; CO_2 fixation; Biofuel; Sunlight.

I. INTRODUCTION

Finding alternative energy resources is a pressing mission for many countries, especially for those countries lacking conventional fuel resources [1]. With the rapid development of the modern industry, the demand for energy has been greatly increased in recent years, and therefore, alternative energy sources are being explored. Biodiesel is produced currently from plant and animal oils. Biodiesel is a transportation fuel that has grown immensely in popularity over the past decade. With the dwindling reserves of fossil fuels, it is now more important than ever to search for transportation fuels that can serve as alternatives to crude oil-based fuels such as gasoline and diesel fuel. Common sources for biodiesel feedstock include soy, sunflower, safflower, canola, and palm. Lately there has been growing controversy about the use of potential food sources for the production of fuel. In attempt to address these concerns, researchers have turned their focus from the popular feedstock and are currently investigating the use of alternative, non-food related feedstock such as oil from algae. Micro algae are sunlight-driven cell factories that convert CO_2 to potential biofuels, foods, feeds and high-value bioactive [2]. Micro algae can provide several different types of renewable biofuels. [3].

The fact that micro algae grow in aqueous suspensions, allows for more efficient access to H_2O, CO_2 and other nutrients which explains the potential for the production of more oil per unit area than other crops currently used. The growth of algae requires

CO_2 as one of the main nutrients. There is an opportunity to sequester CO_2 by using flue gas emissions from industrial sources as the feed for algae cultivation. The objective of the present paper is to summarize the challenges and opportunities of carbon sequestration using micro-algae.

II. OVERVIEW OF MICRO-ALGAE

A. *Why Micro Algae?*

Algae are more efficient at utilizing sunlight than terrestrial plants, [4] consume harmful pollutants, and have minimal resource requirements and do not compete with food or agriculture for precious resources.[5] Algae have higher growth rates than terrestrial plants, allowing a large quantity of biomass to be produced in a shorter amount of time in a smaller area. Algae growth rates of 10 to 50 g m-2 d-1 (grams of algal mass per square meter per day) have been published in the literature. [6] Compared to terrestrial plants such as corn and soy, algae have shorter harvest times because they can double their mass every 24 hours. [2] These short harvest times allow for much more efficient and rapid production of algae compared to corn or soy crops. The yields of different oil producing feedstock can be examined, as shown in Table 1.

B.Resource requirements for algae growth

One of the most compelling advantages of using algae as a biofuel feedstock is that the resource requirements are less intensive compared to other crops and plants. Algae require only a few basic resources to grow successfully: CO_2, water, sunlight and nutrients. Sunlight is normally abundant throughout most of the year and utilized more efficiently than terrestrial crops. CO_2 can be obtained in high concentrations from power plants and industrial processes, or at ambient concentrations from the atmosphere. Algae will grow in most water sources with varying pH levels from fresh drinking water, saline or brackish aquifers and wastewater effluent. [8] Brackish, or moderately salty water, is abundant and provides a suitable environment and resource for algae to grow in. Algae, by virtue of photosynthesis, are adept at sequestering CO_2 or nitrogen oxides from the atmosphere.[9].There is potential to effectively reduce the amount of carbon dioxide and nitrogen oxides released into the atmosphere from many stationary emitters by feeding the carbon-rich flue gas to the algae. [10] Based on a theoretical ratio, Algae are able to fix approximately 1.8 kg of CO_2 fixed for every 1 kg of algae biomass produced. [2]

C. Selection of algae species

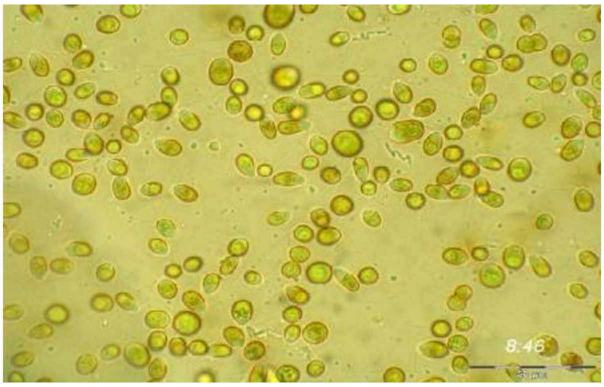
Algae can be oil-rich organisms. Oil content, the percentage of oil per weight of dry biomass, typically ranges from 20 to 50% depending on the species. [2] This oil is composed of many different types of lipids that can be processed easily into biodiesel, jet fuel or other chemicals. Algae species and their typical biomass yield are presented in Table 2. Figure 1 shows micrograph of two algal species

TABLE 1 OILYIELD OF VARIOUS FEEDSTOCK *[7]*

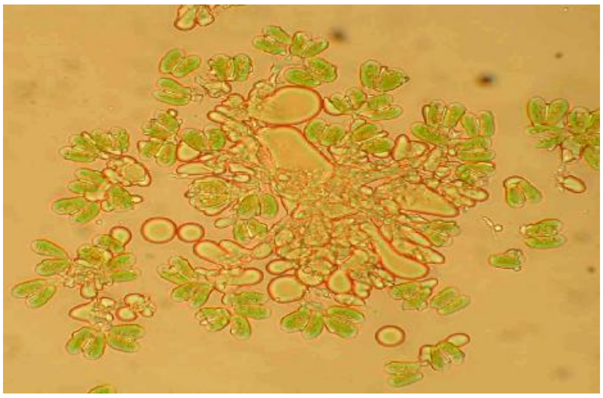
Feedstock	Liters/Hectare
Castor	1413
Sunflower	952
Palm	5950
Soya bean	446
Coconut	2689
Algae	100000

TABLE 2. ALGAE SPECIES AND TYPICAL BIOMASS YIELD. [2]

Species	*Yield* (g/m^2/day)
Marine Nannochloropsis	20
Spirulina plantesis	10.3
Dunaliella salina	12.0
Scenedesmus species	13.4
Ankistrodesmus	18
Haematococcus pluvialis	3.8



(a) Dunaliella salina



(b) Botryococcus braunii

Figure. 1 Micrograph of Algal Species at 400 x magnification

Compared to terrestrial crops such as corn, soy or even palm plants, algae are far more oil-rich and offer a higher yield of oil per unit of land in a year. The main components of algae are carbohydrates, proteins, and lipids. [11] Of particular interest are the lipids, which can be processed into valuable fuel products such as biodiesel (through transesterification), jet fuel, and even traditional gasoline and diesel depending on the species. Lipids produced from algae contain saturated and polar lipids, which are suitable for use as a fuel feedstock and are contained in higher concentrations than other plants. [12] There are many varieties of micro-algae; each species has a different proportion of lipids (fats), carbohydrates and proteins. Some algae strains may contain up to 70 percent lipids making them very suitable for the production of liquid fuels.

D.Photosynthetic efficiency of Micro-algae

The photosynthetic efficiency (*PE*) is defined as the fraction of light energy fixed as chemical energy during photoautotrophic growth. In photosynthesis only light of wavelengths between 400 and 700 nm is used, this represents 43% of the energy of the total spectrum of sunlight and it is called photosynthetic active radiation (PAR). **Fig 2 shows solar spectrum and visible range Minimally** 8 light photons (quanta) are required to produce one mol of O_2. The average energy content of these quanta is 218 kJ/mol quanta combining all these data it is calculated that maximally 11% of sunlight energy (considering all wavelengths) can be converted into chemical energy as biomass. Based on solar irradiation data available at a particular site, the maximum theoretical biomass productivity can be calculated e.g. in the southern India its is 240 tonnes. ha^{-1}. $year^{-1}$. [13] However in practical conditions only 3-6 percent photo conversion efficiency is possible.

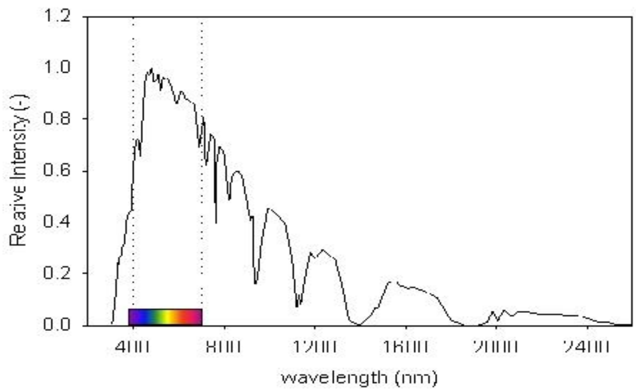


Figure 2.Solar spectrum

E.Cultivation of micro-algae

Algae are typically found growing in ponds, waterways, or other locations that receive sunlight, water and CO_2. Growth depends on many factors and can be optimized for temperature, sunlight utilization, pH control, fluid mechanics and more [14, 15]. Manmade production of algae tends to mimic the natural environments to achieve optimal growth conditions. There are 3 ways to grow and harvest micro-algae for mass production;

Open Pond System – Open ponds are simple expanses of water recessed into the ground with some mechanism to deliver CO_2 and nutrients .open pond are provided with a paddle wheel to allow the algae to circulate. These designs suffer from low yield due to poor mixing and contamination, as well as use huge amounts of water

Closed Photo Bio-Reactors (PBR) – Closed photo bioreactors are a broad category referring to systems that are enclosed and allowing more precise control over growth conditions and resource management. They are made of translucent glass or plastic designed to grow algae in optimum conditions. They are capable of better mixing and more controlled conditions make them superior in terms of both yield and water usage but are very expensive to build and maintain

Hybrid System – It is a combination of PBR and Open pond system to maximize productivity and for optimum utilization of land.

A practical example of a current microalgae production process is Spirulina, a microalga already produced commercially in open ponds in many countries around the world. In these production systems, the algae are cultivated in large (typically 0.2 –0.4 hectares), raceway-type open ponds mixed by paddle wheels. Nutrients, most importantly CO_2, are added to the ponds and these filamentous algae are then harvested by fine mesh screens, spray dried and sold as specialty human foods and animal feeds. Designs of open pond systems and photo bioreactor are shown in Figure 3. The main advantage of using pond systems is that the technology is very well known and various commercial systems already exist. Table 3 presents a short comparison of open pond systems and closed photo bioreactors.

TABLE 3.COMPARISON OF OPEN AND CLOSED SYSTEMS

Parameter	**Open Raceway pond**	**Closed Photo bioreactor**
Scale	Large & Pilot Scale	Laboratory Scale
Cost	Cheaper to construct.	More expensive
Usage	Commercial	Not commercial
Typical cost of biodiesel	2.-2.5 USD/L	5-6 USD/L
Light utilization	Poor	Very high
$C0_2$ losses to atmosphere	High	Almost none
Typical Biomass Yield (g/m^2-day)	10-60	60-100
Area requirement	Large	Small

(a) Open Raceway Pond

(b) Photo-bioreactor

Figure 3.Algae Cultivation Methods [16, 17]

F. Algae harvesting and oil extraction

Production of oil from algae is a straightforward process consisting of growing the algae by providing necessary inputs for photosynthesis, harvesting/dewatering and oil extraction. In order to extract the valuable lipids from within the algae cells a series of steps must be undertaken to isolate the algae cells and oil .A diagram of the overall growth and harvesting process is presented in Figure 4. The traditional process begins by separating the algae biomass from the water broth in the dewatering stage using either centrifuges, filtration or flocculation techniques. Centrifuges collect biomass by spinning the algae-water broth so that water is flung away from the algae cells. Flocculation involves precipitating algae cells out of solution so that they can be removed out of solution. Once the algae cells have been collected the oil must be removed from the cells. Once the oil is removed it can be processed into biodiesel, jet fuel, ethanol, synthetic fuels or other chemicals. There are many methods for algae oil extraction it all depends upon which cheap resources are available near site to make it energy efficient. Solvent or mechanical extraction processes are energy efficient. Any quantity of algae biomass can be conveniently and economically sun dried to remove water. Sun drying prevents nutrient loss since protein, fat and carbohydrates are expected for animal feed purpose. Another good option is to use waste heat from the power plant for algae drying. Algae cultivation & harvesting away from the power plant site may not be energy efficient as algae cake has 50-70% water content that drain a lot of energy from the process before the oil is extracted**.** The harvested algae can be processed by various methods to yield valuable products.

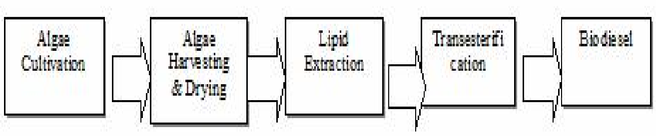


Figure 4. Algae growth and harvesting process. [18].

Microalgae contain fats, carbohydrates, and proteins of which 70% of the total fat content can be directly harvested by mechanical press. The amount of algae harvested is a factor depended on the biomass productivity per square meter per day.There are several options for energy production using micro-algae as shown in Table 4.

TABLE 4.DOWN STREAM PROCESSING OPTIONS

Downstream Processing options	
Processing Step	**Final Product**
Drying	Biomass for animal feed
Extraction and Transesterification	Biodiesel
Fermentation	Ethanol
Anaerobic digestion	Methane
Gasification	Hydrogen

III ALGAE FOR CARBON SEQUESTRATION

The CO_2 sequestration can be accomplished through two ways: i) direct sequestration, which comprises the capture of CO_2 from the exhausted gases from fixed industrial sources, before its emission to atmosphere, and its subsequent storage; and ii) indirect sequestration, based on the capture of CO_2 that is already in the atmosphere, through the stimulation of natural processes just like the photosynthesis that occurs in the superior vegetables, the forests.

Energy from the Biomass via CO_2 sequestration using micro-algae is one of the most important components to mitigate greenhouse gas emissions. Biological Sequestration is a concept based on capturing the total (process + combustion) CO_2 emitting from a thermal power plant via growing micro algae which is used to produce bio-fuel, and its residue can be burned as solid biomass, as well. However, contrary to what is often stated, CO_2 capture by algal cultures is not a CO_2 sequestration or greenhouse gas abatement process. That can only come from converting the algal biomass to biofuels and their use in replacing fossil fuels. As a mitigation strategy, Micro-algae offer the advantage of allowing the continued use of the well-established fossil fuel infrastructure. A Sustainable approach to the capture and disposal of CO_2 should remove and retain CO_2 from the atmosphere in a self sustaining manner. The simple, direct method of greenhouse mitigation is the removal of CO_2 from stack gases followed by long-term sequestration of CO_2 by microalgae ponds.Microalgae CO_2 sequestration is technically feasible and carbon neutral energy alternatives Transition to algal biomass can deliver development and climate co-benefits. The main steps in this process for a standard fossil-fuel power plant are shown in Figure 5 below.

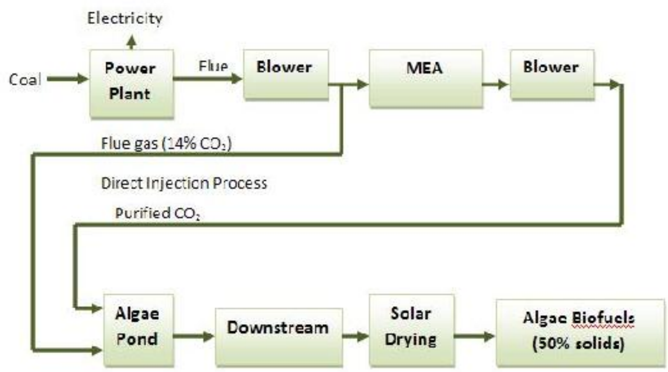


Figure.5 Micro-algal CO_2 sequestration from stationary combustion systems [2]

Based on the literature, one can determine that approximately 40 ha of algae ponds are required to fix the carbon emitted from one MW of power generated from a coal plant at 50% capture efficiency [14] The carbon used to create lipids in the algae is still released into the atmosphere upon combustion of the fuel, but the overall amount of carbon has been used twice: once for energy production in a power plant and second to grow algae for transportation fuels. An ideal methodology for photosynthetic sequestration of anthropogenic carbon dioxide has the following characteristics: (1) a high rate of CO_2 uptake and mineralization of CO_2, (2) resulting in permanently sequestered carbon, (3) produce revenue from sale of high value products, and (4) use of concentrated, anthropogenic CO_2 before it enters the atmosphere.

IV CASE STUDY OF NEYVELI THERMAL POWER STATION

To evaluate the importance of such a process, let's assume that typical Indian Thermal power plants of 500 MW are combined with Algae Pond Systems. Flue gas can be sent directly to pond or CO_2 can be first separated before being injected.MEA solvent can be used to separate CO_2 from flue gas. Flue gas or pure CO_2 can be injected in the form of bubbles. Several studies establish that around 80% can be captured. Based on the previous experimental work [19,20] for every 1 g of algae biomass produced, 1.8 g of CO_2 was utilized (this is on the assumption that algae biomass consists of ~50% carbon) Since carbon is 27.3% of the weight of CO_2, it requires approximately 1.8 times the weight of produced biomass in CO_2. A mass balance of algae pond is shown in figure 6.

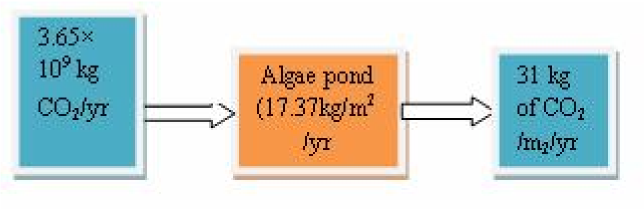


Figure 6. Mass balance of Algae pond

A case study of 500 MW Neyveli Thermal Power plant:
Availability factor for Algae Pond= 85%.
Estimated annual average productivity= 56 gm/m^2-day (for practical conditions)
Overall system productivity= 56 x 0.85 x 365 = 17.37 kilograms per square meter per year
Amount of CO_2 Consumed = 17.37 * 1.8 = 31 kg of CO_2 per square meter growing area per year.
CO_2 emission from the power plant= 10 x 10^6 kg CO_2/day
CO_2 emitted from power plant per year =3.65x10^9kg/yr.
Total Hectares of land required= 11774.19 Hectares
Standard Algae farm size: 100 hectares (247 acres)
No of algae Pond required: 118
The algae farms can be built in multiple units of the 100-hectare standard near thermal power plants where more CO_2 is available. Based on the literature, one can determine that approximately 40 ha of algae ponds are required to fix the carbon emitted from one MW of power generated from a coal plant. [21]. Here, it will be interesting to compare the CO_2 assimilation capacities of micro algae pools and forests considering that 54,200 km^2 forest is needed to assimilate 1,62,60,000 ton CO_2/year while only 10,000 km^2 land is necessary for capturing 12,0000000 ton CO_2/year via micro-algae.

V. ECONOMIC ANALYSIS OF MICRO-ALGAL CO_2 SEQUESTRATION SYSTEM

Algae production requires a site with favourable climate, available water (which can be saline, brackish or wastewater), a ready and essentially free source of CO_2, nearly flat land, and with a clay soil or liner, as plastic liners would be too expensive. The critical issue, after technical feasibility, that is the actual ability to reliably cultivate algal strains that can produce biomass at reasonably high productivities, is the overall capital and operating cost of these production systems. Even assuming that high biomass productivities are possible and stable cultivation achievable, the major problem is likely the irreducible minimal costs of large-scale cultivation systems, including the needed infrastructure, processing, waste treatment, water supply and other support systems required. So, a Prior economic-engineering feasibility analyses have been done.

Land area required : 130ha
Biomass Productivity : 56g/m^2/day
Annual Algae Yield @300 days of operation: 168tonnes/ha/yr
Algae Biomass yields from 100 ha @168 T/ha/yr : 16800 T
Oil from Biomass (20%) ; 3,360,000 lit
Residue from Biomass, (80%) 13,440,000 kg
Revenue from crude algae oil@ Rs.19/lit (based on crude oil @US $60) : Rs.6.384 crores
Revenue from Residues @ Rs10/kg Rs.13.44 crores
Revenue from carbon credit @ Rs.1400/tonne of CO_2 fixed (1.8 tonnes of CO_2 is fixed by 1 tonne of Algal biomass) : Rs.1400x1.8x 16800: Rs 4.23 crores
Total Revenues : Rs 24.054 crores

A conservative estimate of Capital cost & operating cost is assumed
Fixed investment 100 Cr
Operational cost 20 Cr
Simple payback period = Investment /Annual Revenues = 120/24.054 = 5yrs

C0$_2$ Sequestration and Algal energy production at power plants helps to reduce CO_2 emissions, reduce the need to import oil, and generates employment. Micro-algal based carbon sequestration technologies can, in principle, not only cover the cost of carbon capture and sequestration but also produce environment-friendly bio-fuel.

VI CHALLENGES INVOLVED IN MICRO-ALGAL CARBON SEQUESTRATION

The various challenges involved in micro-algal Carbon Sequestration are as follows:

- Low actual photosynthetic efficiency and Productivity of Micro-algae.
- No Practical experience on large scale algal cultures for Sequestration (thousands of hectares).
- Large variability in performance among various cultures and difficulty to standardize the cultivation techniques.
- Technology depends on Availability of many input sources like combustion gas, Salty and waste water.
- Instability of the culture to maintain the desired species.
- A Negative Net energy ratio (due to high energy consumption of water pumping, CO2

distribution, mixing and harvesting etc).Therefore higher value co-products are needed for economic viability.

- Higher Social and Ecological impacts of large Scale facilities.
- Need of High level expertise with diverse engineering background.
- Due to lack of industrial scale experiments, there is insufficient knowledge about the Energy balance, GHG Balance, CO_2 abatement potential and economic viability.
- Areal productivity using open raceway ponds will encounter upper limits related to the amount of light that penetrates the water surface, and lipid content.
- High cost associated with Photo bioreactors.

VII CONCLUSION

Carbon dioxide utilization & sequestration is a newly-emerging field with substantial room to expand in the future. By coupling algae production with a CO_2 pollution control process, the economic viability of micro algal based biodiesel is significantly improved. The CO_2 fixation using algae & to harvest algae for bio-fuel has not yet been undertaken on a commercial scale, but feasibility studies have been conducted to arrive at the above yield estimate. According to the evaluations already presented, we can conclude that Micro algal sequestration may be a possible solution for reduction in CO_2 emissions. In spite of its limitations, algal carbon Sequestration technology is beneficial due to the following facts and figures:

- Carbon sequestration technologies could be incorporated and best applied in connection with large-scale energy conversion plants such as coal power plants and oil refineries in the country.
- CO_2 Sequestration using micro-algae will provide a global opportunity to reduce CO_2 emissions. Algal sequestration may act to slow impacts of global warming and will not contribute to additional CO_2 emissions.
- Theoretically, there is enough land to grow algae for carbon sequestration in India but land is unlikely to be available near the Power plants.
- The algal based technology is very much competitive with more advanced and emerging renewable technologies such as wind, solar, geothermal, and other forms of biomass in reducing GHG emissions.
- Both Carbon Sequestration and bio-diesel production from micro algae are popular R&D subjects with some successful pilot scale applications. They are carbon neutral and producing and using them has little or no impact on the environment
- By assessing the viability of algae from a true technical perspective, it is clearly apparent that Micro algae will be the only solution to mitigate Global warming.
- Research on algal -based sequestration is still in the beginning stages in India. Developing & commercialization of these technologies requires a focused, comprehensive, and well-funded R&D program.

ACKNOWLEDGMENTS:

This research was funded by DST, Govt of India under National Program on Carbon sequestration research Award Number DST/IS-STAC/CO2-12/OR.

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