Review Article

ALGAECULTURE: AN ALTERNATIVE TO SOLVING ENERGY SUSTAINABILITY CRISES IN DEVELOPING COUNTRIES

ABSTRACT

There is an impending need to reduce the dependency on fossil fuels in these areas of the world considering the ever depleting conventional oil resources and climate change, induced by greenhouse gas emissions. Algae are currently being prompted as an ideal next generation bioenergy feedstock due to the fact that they do not compete with food or feed crops. They also produce much higher areal oil yields than the current agricultural crops. They can be produced on barren lands and have broad bioenergy potentials as they can be used to produce liquid transportation and heating fuels such as biodiesel and ethanol, or anaerobically digested to produce biogas. Algae are fast growing organisms capable of fixing high amount of carbon dioxide through photosynthesis to produce biomass**.** Diverse technologies are currently being pursued to produce algae for bioenergy applications.

KEYWORDS: **Algae, Biofuel, Greenhouse, Bioenergy, Feedstock**

INTRODUCTION

Escalating fuel prices, the emerging concern about global warming that is associated with burning fossil fuels, quest for economic growth, fighting poverty and the growing demand for petroleum products have spurred new interest in the search for alternative sources of natural oil for fuel (Abubakar *et al*., 2012).Microalgae are photosynthetic microorganisms that convert sunlight, water and carbon dioxide to algal biomass. Many microalgae are excitingly rich in oil (Chisti, 2007) which can be converted to biodiesel using existing technology. Microalgae are fast growing unicellular or simple multicellular microorganism which have the ability to fix carbondioxide(CO_2) while capturing solar energy at an efficiency 10 to 50 times greater than that of terrestrial plants and higher biomass production compared to energy crops (Wang *et al.*, 2008). Microalgae areknown for their rapid growth and high energy content. The main environmental factors influencing micro algal growth and chemical composition are light, nutrients, temperature and pH (Rousch *et al.,* 2003). Microalgae have several advantages, including higher photosynthetic efficiency as well as higher growth rates and higher biomass production compared to other energy crops. Several micro algae strains have been reported to have the ability to accumulate large quantities of lipids. It has also been observed that nitrogen limitation leads to an increase of lipid content in some chlorella strains (Reiten *et al.*, 1994).Previous studies have confirmed that lipid content in some micro algae strains could be increased by various cultivation conditions (Illman *et al.*,2000),under stress conditions a lipid production of 30%-60% of dry cell weight has been reported, one can only imagine the yields under favourable conditions. Since fatty acid methyl esters originating from vegetable oils and animal fats are known as biodiesel, from the energetic point of view, lipids are the most desirable components of microalgae cells (Sostaric *et al.*,2009). In addition the organic matter produced by photosynthetic microalgae can be transformed into a wide range of valuable products, such as biodiesel, food additives and health-care products (Pulz and Gross, 2004). Algal-oil processes into biodiesel as easily as oil derived from land-based crops.Algae have much faster growthrates than terrestrial crops. The per unit area yield of oil from algae is estimated to be from between 5,000 to 20,000 gallons (18,927 to 75,708 litres) per acre, per year; this is 7 to 31 times greater than the next best crop, palm oil (635 gallons *or* 2,404 litres). Many companies are pursuing the development of algae bioreactors for various purposes, including biodiesel production and CO_2 capturing (Veridium Patents Yellowstone, 2007). This paper highlights the potential of microalgae for sustainably providing biodiesel for displacement of petroleum-derived transport fuels, such as gasoline, jet fuel and diesel.

Algae Cultivation

Raceway Ponds

A raceway pond is made of a closed looprecirculation channel that is typically about 0.3m deep. Mixing and circulation are produced by apaddlewheel. Flow is guided around bends bybaffles placed in the flow channel. Raceway channelsare built in concrete or compacted earth, and may belined with white plastic.. Broth is harvested behindthe paddlewheel, on completion of the circulation loop.The paddlewheel operates all the time to preventsedimentation.Raceway ponds for mass culture of microalgae havebeen used since the 1950s. Extensive experience existson operation and engineering of raceways. Evaporative water loss can besignificant. Because of significant losses to atmosphere,raceways use carbon dioxide much less efficiently thanphoto-bioreactors. Productivity is affected by contaminationwith unwanted algae and microorganisms thatfeed on algae. The biomass concentration remains lowbecause raceways are poorly mixed and cannot sustainan optically dark zone.Raceways are perceivedto be less expensive than photo-bioreactors, because theycost less to build and operate. Although raceways arelow-cost, they have a low biomass productivity comparedwith photo-bioreactors.

Photo-bioreactors

Unlike open raceways, photo-bioreactors permitessentially single-species culture of microalgae forprolonged durations. Photo-bioreactors have been successfullyused for producing large quantities of microalgalbiomass (Carvalho *et al.*, 2006).

A tubular photo-bioreactor consists of an array ofstraight transparent tubes that are usually made of plasticor glass. This tubular array, or the solar collector, iswhere the sunlight is captured (Fig. 1). The solar collector tubes are generally 0.1m or less in diameter. Tubediameter is limited because light does not penetrate toodeeply in the dense culture broth that is necessary forensuring a high biomass productivity of the photo-bioreactor.

Microalgal broth is circulated from a reservoirto the solar collector and back to the reservoir.

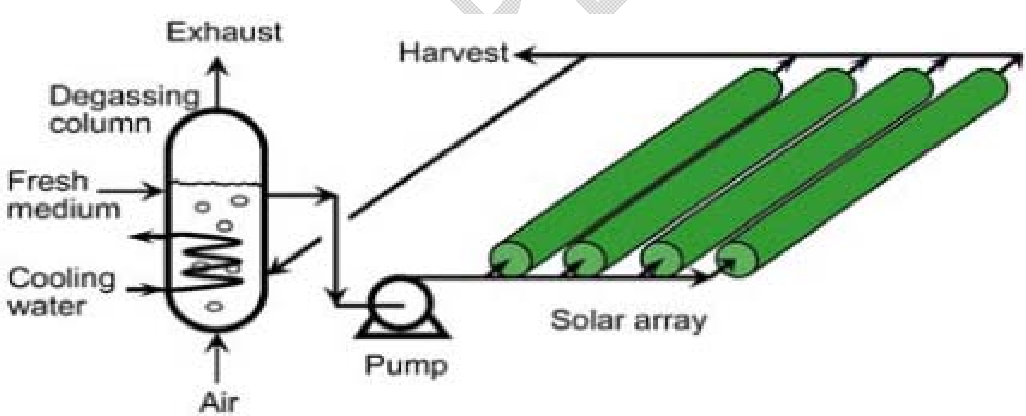

Figure 1: A tubular photobioreactor with parallel run horizontal tubes

The solar collector is oriented to maximize sunlightcapture (Molina *et al.*, 1999; Sánchez *et al.*, 1999). In a typical arrangement, the solar tubes areplaced parallel to each other and flat above the ground (Fig. 1). Horizontal, parallel straight tubes are sometimesarranged like a fence, in attempts to increase thenumber of tubes that can be accommodated in a givenarea. The ground beneath the solar collector is oftenpainted white, or covered with white sheets of plastic (Tredici, 1999), to increase reflectance, or albedo.A highalbedo increases the total light received by the tubes. Biomass sedimentation in tubes is prevented bymaintaining highly turbulent flow. Flow is producedusing either a mechanical pump (Fig. 1), or a gentlerairlift pump. Mechanical pumps can damage the biomass (Mazzuca *et al*., 2006), but are easy to design, install and operate.

Table 1: Comparison of photo-bioreactor and raceway production methods

VARIABLE	PHOTO-BIOREACTOR FACILITY	RACEWAY PONDS
Annual biomass production (kg)	100,000	100,000
Volumetric productivity ($kg/m^3/d$)	1.535	0.117
Areal productivity ($kg/m^2/d$)	0.048[a] 0.072[c]	0.035[b]
Biomass concentration in broth (kg/m^3)	4.00	0.14
Area needed (m^2)	5681	7828
Oil yield (m^3/ha)	136.9[d] 58.7[e]	99.4[d] 42.6[e]
Annual CO_2 consumption (kg)	183,333	183,333
Number of units	6	8

[a] Based on facility area.

[b] Based on actual pond area.

[c] Based on projected area of photo-bioreactor tubes.

[d] Based on 70% by wt oil in biomass.

[e] Based on 30% by wt oil in biomass.

(Christi, 2007)

Algae Oils

Oil content of some microalgae exceeds 80% of the dry weight of algae biomass. Agricultural oil crops, such as soybean and oil palm, are widely being used to produce biodiesel; however, they produce oils in amounts that are miniscule (e.g. less than 5% of total biomass basis) compared with microalgae (Chisti, 2007). As a consequence, oil crops can provide only small quantities of biodiesel for blending with petroleum diesel at a level of a few percent, but they are incapable of providing the large quantities of biodiesel that are necessary to eventually displace all petroleum-sourced transport fuels (Chisti, 2007).

A conceptual process for producing microalgal oils for making biodiesel is shown in Plate 1. The process consists of a microalgal biomass production step that requires light, carbon dioxide, water and inorganic nutrients. The latter are mainly nitrates, phosphates, iron and some trace elements. Sea water supplemented with commercial nitrate and phosphate fertilizers, and a few other micronutrients, is commonly used for growing marine microalgae (Molina *et al*., 1999).

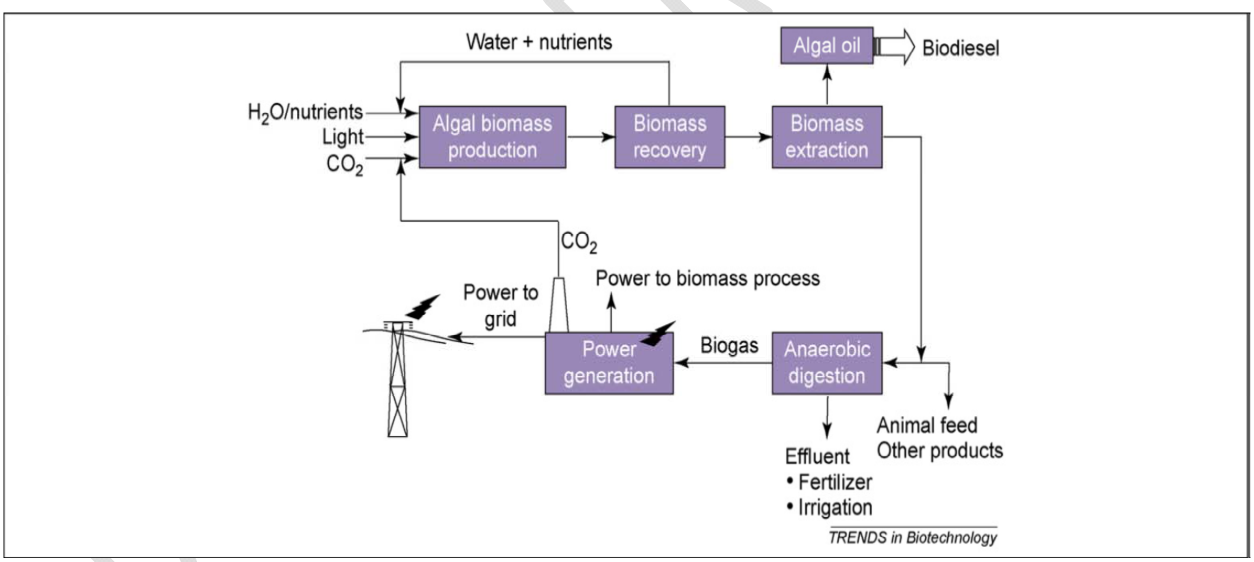

Plate 1: A conceptual process for producing microalgal oil for biodiesel

Approximately half of the dry weight of the microalgal biomass is carbon (Sanchez. *et al*., 2003), which is typically derived from carbon dioxide. Therefore, producing 100 tons of algal biomass fixes roughly 183 tons of carbon dioxide. This carbon dioxide must be fed continually during daylight hours. Microalgal biomass production can potentially make use of some of the carbon dioxide that is released in power plants by burning fossil fuels (Sawayama *et al*., 1995). The

algal broth produced in the biomass production stage needs to be further processed to recover the biomass (Molina *et al*. 2003). The water and residual nutrients recovered at this stage can be recycled to the biomass-cultivation. The concentrated biomass paste is extracted with a water-immiscible solvent to recover algal oil, which can then be converted to biodiesel. The biomass residue that remains after extraction of oil could be used partly as high-protein animal feed and, possibly, as a source of small amounts of other high-value microalgal products (Gavrilescu and Chisti, 2005). In both scenarios, the revenue from selling the biomass residues could defray the cost of producing biodiesel. However, the majority of algal biomass residue from oil extraction is expected to undergo anaerobic digestion to produce biogas. The carbon dioxide generated from combustion of biogas can be recycled directly for the production of the microalgae biomass.
Energy content of biogas produced through anaerobic digestion typically ranges from 16200kJ/m^3 to 30600kJ/m^3(Wulf, 2005) depending on the nature of the source biomass. Typically, the yield of biogas varies from 0.15 to 0.65kg of dry biomass (Wulf, 2005). Assuming average values of biogas energy content and yield, biogas production from microalgal solids, after their 30% oil content has been removed, could provide at least 9360MJ of energy per metric ton. This is a substantial amount of energy and it should run the microalgal biomass production process.The total content of lipids in microalgae vary from about 1-85% of the dry weight (Rodolfi *et al*., 2009) with values higher than 40% typically achieved under nutrient limitation.

Algae for Biofuels

Algae for biofuels have been studied for many years for production of hydrogen, methane, vegetable oils (triglycerides, for biodiesel), hydrocarbons and ethanol. Methane was the focus of most of the early work in microalgae biofuels production, when microalgae were considered mainly for their applications in wastewater treatment. More simply would be the production of starch by microalgae and its subsequent fermentation by yeasts, as practiced with cane sugar and corn starch in fuel ethanol production. Such an approach, however, would compete with very low-cost sugar and starch produced by higher plants. It is, however, not all that different in concept from the production of vegetable oils, triglycerides specifically, which is the focus of almost all the current interest in algae biofuels.

Bioenergy Conversion of Algae

Biomass from micro- and macroalgae can be converted into solid, liquid or gaseous energy carriers but there are some major differences in the chemical and physical chemical composition of algae as well as their physical composition which make them more or less suitable for a given conversion technology.

In general the most important issues to remember when evaluating bioenergy conversion technologies for algae are their high content of inorganics (more than 30% can be found), a low level of fermentable sugars, high protein and sulphur content and a potentially very high content of oils. The glycerine has many uses, such as in the manufacture of food, in the production of pharmaceuticals as well as a feedstock for biogas.

Algae Biodiesel

The term bio-diesel covers diesel type oil made from vegetable oils. In plants oils are found as triglycerides, where three fatty acids of different chain lengths are coupled to a glycerol molecule by ester bonds. By splitting the triglycerides into their components via a transesterification reaction the single fatty acids can be separated for used as fuel in diesel engines. In principle the plant oils can be used directly as diesel fuels, but triglycerides have a high melting point and can be solid at low temperatures.

Algae ethanol

The production of ethanol by fermentation of sugars is technically well developed. On commercial scale the sugar glucose is fermented by ordinary yeast to produce ethanol. Glucose is a so called C6 sugar with 6 carbon atoms and can be found in a number of different plant sugars of which cellulose, starch and sucrose are the most common. New microorganisms capable of fermenting C5 sugars are under development, but have not yet reached a commercial scale and applicability.

Combustion

Efficient combustion of biomass requires a low content of inorganic components as well as of nitrogen and sulphur compounds. The chemical composition of algae biomass shows that it is not a suitable feedstock for combustion. Raw algae biomass is thus not suitable for heat and electricity production by combustion. No reports on combustion of algae biomass have been found.

Biogas

Biogas is produced by methanogenic bacterial breakdown of organic matter under anaerobic conditions. It is also known as anaerobic digestion or mesophilic fermentation, and consists of at least three bacterial processes yielding the main final products methane (CH_4) and CO_2. A wide range of organic matter can be converted in a biogas reactor, with lignin and cellulose being the main exceptions. The processing of biomass in a biogas reactor typically takes weeks, but the process as such is robust. The composition of biogas varies depending upon the feedstock. Biogas will contain CH_4, CO_2, H_2, N_2, O_2, H_2S and water vapour. Typically the methane content of biogas is 55-75% CH_4, 20-40% CO_2 and smaller amounts of the other gases. Purification of the gas is therefore needed and several large-scale methods are available. Following the conversion to biogas there will be residual liquid and fibre fractions. The liquid fraction typically has a high content of salts and nitrogen, whereas the fibre fraction contains the biomass that could not be digested by the bacteria.

Biogas production from of algae by methanogenic bacteria is probably the best suited technology for converting both macro- and microalgae biomass into a practical energy carrier.

Algae Harvesting and Strains

The basic concept of algal oil production is to use relatively small (in total area) photo-bioreactors to produce a modest amount of “inoculum” culture (about 1-2 % of the total biomass produced) to seed much larger, totaling several hundred hectares, open ponds. The biomass would need to be concentrated by an initial factor of at least about thirty-fold, requiring very low-cost harvesting processes, such as “bioflocculation”, a spontaneous flocculation-sedimentation of the algal cells, using no, or at most very little, flocculation chemicals. Such low-cost harvesting processes must be developed and demonstrated for each algal species and even strain. At present there are no low-cost harvesting technologies available. The algal strains to be cultivated would be selected based on many criteria, of which oil content, productivity, and harvestability would be primary, but also resistance to contamination, tolerance of high oxygen levels and temperature extremes, and adaptation to the local water chemistry and other local conditions experienced by the algal cells in the growth ponds. Figure 2 shows microalgal biomass being recovered from the culture broth by filtration

After harvesting, further concentration and oil extraction is required, for which various processes are proposed, including cell breakage and solvent extraction, possibly using a three phase centrifugation.

Figure 2: Microalgal biomass recovered from the culture broth by filtration

Biodiesel Production

Parent oil used in making biodiesel consists oftriglycerides in which three fatty acidmolecules are esterified with a molecule of glycerol.In making biodiesel, triglycerides are reacted withmethanol in a reaction known as trans-esterification oralcoholysis. Trans-esterification produces methyl estersof fatty acids that are biodiesel, and glycerol (Figure3).

The reaction occurs stepwise: triglycerides are firstconverted to diglycerides, then to monoglycerides andfinally to glycerol.

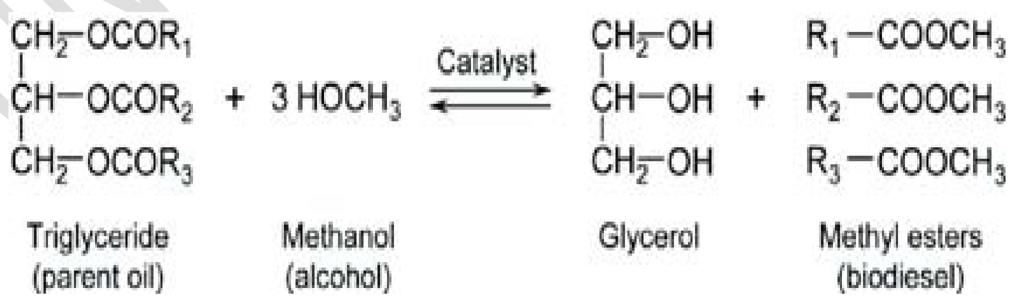

Figure 3: Trans-esterification of oil to biodiesel (R1–3 are hydrocarbon groups).

Trans-esterification requires 3 mols of alcohol for each mole of triglyceride to produce 1 mol of glycerol and 3 mols of methyl esters (Fig. 3). Industrial processes use 6mol of methanol for each mole of triglyceride (Fukuda *et al*., 2001). Yield of methyl esters exceeds 98% on a weight basis (Fukuda *et al*., 2001).

Trans-esterification is catalyzed by acids, alkalis (Meher *et al*., 2006) and lipase enzymes (Sharma *et al*., 2001). Alkali-catalyzed trans-esterification is about 4000 times faster than the acid catalyzed reaction (Fukuda *et al*., 2001). Alkali-catalyzed trans-esterification is carried out at approximately 60°C under atmospheric pressure; as methanol boils off at 65°C at atmospheric pressure. A higher temperature can be used in combination with higher pressure, but this is expensive. Methanol and oil do not mix; hence the reaction mixture contains two liquid phases.

The main advantages with producing micro algae for energy production are:

- Does not compete with agriculture
- High per acre yield
- Contains no Sulphur therefore no SO_2 emissions
- Nontoxic and highly biodegradable
- Does not require soil for growth
- Uses as little as 8cm of water per year
- Adaptable anywhere even at great distances from water.
- Industrial emissions of CO_2 from power plants, refineries, and other stationary emitters can be productively consumed by micro algae in engineered plants and used to manufacture valuable products, thus making the whole process carbon neutral.

Hundreds of species of micro algae are being experimented with, such as*Arthrospira platensis* (spirulina) which is easy to culture and easy to harvest but does not contain a high oil content and*Haematococcus pluvialis* (red algae), which is very high in oil yield. With the correct species in place and the right conditions the species can produce oil at near-theoretical limits

Table 2: Oil content of some microalgae

MICROALGA	OIL CONTENT (% DRY WT)
Botryococcus braunii	25–75
Chlorella sp.	28–32
Cylindrotheca sp.	16–37
Isochrysis sp.	25–33
Nannochloropsis sp.	31–68
Schizochytrium sp.	50–77

Modified from Chisti (2007).

Economics of Biodiesel Production

Recovery of oil from microalgal biomass and conversion of oil to biodiesel are not affected by whether the biomass is produced in raceways or photo-bioreactors. Hence, the cost of producing the biomass is the only relevant factor for a comparative assessment of photo-bioreactors and raceways for producing Microalgal biodiesel. For the facilities detailed in Table 1, the estimated cost of producing a kilogram of microalgal biomass is $2.95 (N442.5) and $3.80 (N570) for photo-bioreactors and raceways, respectively (Chisti, 2007). If the annual biomass production capacity is increased to 10,000 tonnes, the cost of production per kilogram reduces to roughly $0.47 (N70.5) and $0.60 (N90) for photo-bioreactors and raceways, respectively, because of economy of scale. Assuming that the biomass contains 30% oil by weight, the cost of biomass for providing a liter of oil would be about $1.40 (N210) and $1.81 (N271.5) for photo-bioreactors and raceways, respectively (Chisti, 2007). Oil recovered from the lower-cost biomass produced in photo-bioreactors is estimated to cost $2.80/L (N420/L). Biodiesel from palm oil costs roughly $0.66/L (N99/L) or 35% more than petro-diesel. This suggests that the process of converting palm oil to biodiesel adds about $0.14/L (N21/L) to the price of oil. For palm oil sourced biodiesel to be competitive with petro-diesel, the price of palm oil should not exceed $0.48/L (N72/L).

Microalgal oils can potentially completely replace petroleum as a source of hydrocarbon feedstock for the petrochemical industry. For this to happen, Microalgal oil will need to be sourced at a price that is roughly related to the price of crude oil. For example, if the prevailing price of crude oil is $60/barrel (N9000/barrel), then microalgal oil should not cost more than about $0.41/L (N61.5/L), if it is to substitute for crude oil. If the price of crude oil rises to

$80/barrel (N12000/L) as sometimes predicted, then microalgal oil costing $0.55/L (N82.5/L) is likely to economically substitute for crude petroleum.

CONCLUSION

Algal biodiesel is technicallyfeasible. Producing low-cost microalgalbiodiesel requires primarily improvements to algalbiology through genetic and metabolic engineering.

Biodiesel has great potential; however, the high cost and limited supply of organic oils prevent it from becominga serious competitor for petroleum fuels. As petroleum fuel costs rise and supplies dwindle, alternative fuels willbecome more attractive to both investors and consumers. For biodiesel to become the alternative fuel of choice, itrequires an enormous quantity of cheap biomass. Using new and innovative techniques for cultivation, algae mayallow biodiesel production to achieve the price and scale of production needed to compete with, or even replace,petroleum.Algal biomass needed for production oflarge quantities of biodiesel could be grown in photo-bioreactors,but a rigorous assessment of the economics ofproduction is necessary to establish competitiveness withpetroleum-derived fuels. Achieving the capacity to inexpensivelyproduce biodiesel from microalgae is of strategicsignificance to an environmentally sustainable society.

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