The Science of Algal Fuels

Phycology, Geology, Biophotonics, Genomics and Nanotechnology

Edited by

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1. Introduction

Today, all over the world, energy crisis and environmental issues are the most important concern. It is projected that world energy demand will continue to expand by 45% from 2008 to 2030, an average rate of increase in 1.6% per year (World Energy Outlook, 2008). Nearly 81% of the energy supply is from fossil fuels, followed by 16% renewable energy and 2.8% nuclear energy (Fig. 1). Use of fossil fuels as energy is unsustainable due to depleting resources and the accumulation of greenhouse gases in the environment (Demirbas, 2010). Another problem is their uneven distribution in the world where 63% of the global petroleum fuel resources are located in the Middle East with equity, environmental, economic and geopolitical implications (Hacisalihoglu et al., 2009). Biomass-based energy can serve as an alternative energy source to meet the present and future demand, including transportation fuel, although presently only about 0.6% of transportation fuel are supplied as biofuels.

Biofuels include use of solid biomass, biohydrogen, biogas and liquid fuels such as bioethanol and biodiesel. Biological hydrogen production is still in an incipient phase; therefore, the most commonly used biofuels, aside from the burning of solid biomass, are biogas, biodiesel and bioethanol. According to Global Status Report Renewable-2011, about 86 billion litres of bioethanol and 19 billion litres of biodiesel were produced in 2010 compared to 17 billion litres of bioethanol and 0.8 billion litres of biodiesel produced in 2000 (Fig. 2). The USA is the biggest producer of biofuel, followed by Brazil and Germany (Fig. 3). Based on the source of feedstocks, liquid biofuels can be classified into four generations: First-generation biofuels are produced from food crops such as sugar cane, soybeans, cassava, potatoes, maize, etc., and animal fats; second-generation biofuels derived from non-food crops such as Jatropha, tobacco, Miscanthus, switch grass, wood, wheat straw, waste fruit pulp, etc.; third-generation biofuel from algae; and fourth-generation biofuel from genetically engineered organisms (Demirbas, 2011). In this chapter, we discuss various aspects of algal biofuel production through an integrated biorefinery approach.
Figure 1. Global energy consumption (Renewables 2011-Global Status Report).

Figure 2. Bioethanol and biodiesel production, 2000–2010 (Courtesy F.O.Licht, Renewables 2011-Global Status Report).

Figure 3. Top 20 bioethanol and biodiesel producer in the world (Reproduced from Biofuels Platform 2010).
1.1. BIOETHANOL

Ethanol is a high-octane fuel which can be used in various combinations with petrol or gasoline such as E10 or E85 containing 10 and 85% ethanol, respectively. When blended with fossil fuel, bioethanol reduces cancer-causing compounds such as benzene, toluene, xylene and ethyl benzene. Bioethanol can be produced either from sugar, starch or lignocellulosic biomass. Sugar can be directly converted into bioethanol by yeast fermentation, whereas starch first needs to be converted to simple sugar like glucose, through a process called saccharification, before being fermented to ethanol. Production of ethanol from lignocellulosic materials is a more complex process, which is not yet at a commercial stage. Various feedstocks such as sugar cane, corn, cereal grains, potato, sweet potato, cassava and other plant materials are being used for the production of bioethanol all over the world (Fig. 4). World ethanol market is projected to reach around 105 billion litres in 2012 (Martin et al., 2010).

1.2. BIODIESEL

Biodiesel is defined as the monoalkyl esters of vegetable oil and animal fats (ASTM, 2008) and is produced by the transesterification of triglyceride with monohydric alcohols. Biodiesel is generally similar to petroleum-derived diesel in its main characteristics such as cetane number, energy content, viscosity and phase changes (Lin and Tjong, 2010) and can be blended in any proportion with fossil-based diesel. Therefore, biodiesel has become the most common liquid biofuel in the world after ethanol. Biodiesel are mainly produced from vegetable oil such as,
soybean, palm, sunflower oil, followed by biomass-based and non-agricultural feedstock (Demirbas, 2009). (Fig. 5). Huang et al. (2010) claim that biodiesel use can decrease by 90% air toxicity and by 95% cancers resulting from fossil diesel use.

2. Need for Alternative Feedstock for Biofuel

Biofuels offer a potential source of renewable energy and possibly large new markets for agricultural producers. But current biofuel programmes are unsustainable from environmental, economic and societal standpoints. The use of corn, sugar cane and vegetable oil has driven the food versus fuels debate because these feedstocks are components of the human food chain (Mata et al., 2010). Large-scale production of biofuels from crop plants usually damages the environment by the use of harmful pesticides and fertiliser, mostly nitrogen, which reduces the fertility of the soil (Fig. 6). Martin et al. (2010) discussed the repercussion of excessive use of agricultural land and water (Table 1). Water requirements also depend on the geographic, climatic variables and type of feedstock used.

3. Algae for Biofuel Production

Algae a novel biofuel feedstocks have several potential advantages including higher area productivity than traditional crops (Posten and Schaub, 2009; Sahoo, 2010). no competition with conventional agricultural land and utilisation of different water sources (e.g. seawater, brackish water and wastewater). Terrestrial plants in
temperate climates can presently achieve a photo conversion efficiency of only about 1%, while microalgae might in the future convert up to 5% of the solar energy into chemical energy (Schenk et al., 2008). Several microalgae such as Botryococcus, Scenedesmus, Chlorococcum and Chlorella contain significant...
Table 2. Biochemical composition of some biofuel feedstock.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Carbohydrate</th>
<th>Protein</th>
<th>Lipid</th>
<th>References</th>
</tr>
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<tr>
<td><strong>Crop plants</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td>25.4</td>
<td>46.7</td>
<td>71.2</td>
<td>Nikolić and Lazić (2011)</td>
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<td>Jatropha</td>
<td>30.11</td>
<td>32.88</td>
<td>27.36</td>
<td>Azza and Abu-Salem (2016)</td>
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<td>Rapeseed</td>
<td>NA</td>
<td>NA</td>
<td>40.48</td>
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<td>Castor</td>
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<td>NA</td>
<td>43.45</td>
<td>Carioca et al. (2009)</td>
</tr>
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<td>Palm Oil</td>
<td>0.4</td>
<td>0</td>
<td>99.6</td>
<td>Aitchy (1984)</td>
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<td>Sugarcane, bagasse</td>
<td>75–80</td>
<td>1.5–2</td>
<td>&lt;1</td>
<td>Han et al. (1983)</td>
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<td>Maize</td>
<td>66–76</td>
<td>5–13</td>
<td>NA</td>
<td>FAO (1993)</td>
</tr>
<tr>
<td>Cassava</td>
<td>80–85</td>
<td>1–2</td>
<td>Trace</td>
<td>Charles et al. (2005)</td>
</tr>
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<td><strong>Seaweeds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caulerpa lentillifera</td>
<td>44–46</td>
<td>11–12</td>
<td>1–2</td>
<td>Matanjan et al. (2009)</td>
</tr>
<tr>
<td>Ulva lactuca</td>
<td>70</td>
<td>7.06</td>
<td>1.64</td>
<td>Wong and Cheung, 2000</td>
</tr>
<tr>
<td>Eucheuma cottonii</td>
<td>35–36</td>
<td>10–12</td>
<td>1–2</td>
<td>Matanjan et al. (2009)</td>
</tr>
<tr>
<td>Gracilaria cervicornis</td>
<td>63</td>
<td>19.7</td>
<td>0.427</td>
<td>Marinho-soriano et al. (2006)</td>
</tr>
<tr>
<td>Hypnea japonica</td>
<td>57.4</td>
<td>19</td>
<td>1.42</td>
<td>Wong and Cheung, 2000</td>
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<td>Sargassum vulgaris</td>
<td>61</td>
<td>13.6</td>
<td>0.491</td>
<td>Marinho-soriano et al. (2006)</td>
</tr>
<tr>
<td>Laminaria hyperborea</td>
<td>50–52</td>
<td>8.9</td>
<td>&lt;1</td>
<td>Horn (2000)</td>
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<tr>
<td><strong>Microalgae</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Botryococcus braunii</td>
<td>2</td>
<td>40</td>
<td>33</td>
<td>Eduardo et al. (2010)</td>
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<tr>
<td>Prymnesium parvum</td>
<td>25–33</td>
<td>78–45</td>
<td>72–38</td>
<td>Singh et al., 2011</td>
</tr>
<tr>
<td>Isochrysis sp.</td>
<td>15–5</td>
<td>29.5</td>
<td>23.4</td>
<td>Renaud et al. (1999)</td>
</tr>
<tr>
<td>Sprogyra sp.</td>
<td>33–64</td>
<td>6–20</td>
<td>11–21</td>
<td>Denizelbas (2010)</td>
</tr>
</tbody>
</table>

Amount of lipids, whereas macroalgae such as *Sargassum, Laminaria, Asphodellum, Gracilaria* and *Kappaphycus* are higher in their carbohydrate contents which make them possible feedstocks for biodiesel and bioethanol production, respectively (Table 2). (Fig. 7a–d). The use of algae for biofuel was investigated in the USA and Japan as an alternative energy source from the 1970s to 1990s after the oil crisis, but the studies were discontinued when oil prices stabilised (Yokoyama et al., 2007).

3.1. SEAWEEDS FOR BIOETHANOL

Marine macroalgae (seaweeds) lack lignin but contain high amount of carbohydrates which makes them potentially suitable feedstock for the production of bioethanol. The cell wall of algae consists of various forms of complex carbohydrates such as cellulose, hemicellulose, agar, alginate, carrageenan, fucoxan (Kloareg et al., 1986; Goh and Lee, 2010), the latter four being extracted and used in food, personal care products and some industrial applications (Sahoo, 2000). Seaweed industrial wastes, i.e. the remaining pulp after extraction of the high value
polysaccharides, still contain high amount of carbohydrate which may be used as a source of raw material for ethanol production (Kumar and Sahoo, 2012). It will also reduce organic load from sea which was washed and deposed into the sea during phycocolloids extraction process (Ge et al., 2011). Utilisations of seaweeds for bioethanol production are only of economic interest when integrated with a utilisation of the higher value components. Seaweeds and waste products can also be used for biogas production through anaerobic digestion (Gunaseelan, 1997).

3.2. PROCESSING OF SEAWEEDS BIOMASS FOR BIOETHANOL PRODUCTION

Seaweed phycocolloids can be converted into bioethanol, but direct use of these phycocolloids for bioethanol production will not be cost-effective. So, after the extraction of phycocolloids, the remaining pulp can be used for bioethanol production.

Since the pulp contains high amount of carbohydrate and other organic materials, these can be converted into bioethanol through saccharification and fermentation. *Saccharomyces cerevisiae*, a common yeast, and *Zymomonas mobilis*,
a bacterium, are the two most important microorganisms used for bioethanol production (Dumsday et al., 1997), but they have a very narrow substrate range. However, *Pichia angophorae* is a more suitable organism for ethanol production from seaweed extract. It can utilise both substrates, mannitol as well as laminaran, simultaneously (Horn et al., 2000).

Apart from alginate, agar and carrageenan, the cell wall of algae also contains cellulose, fucoidan and protein. Anaerobic degradation of fucoidan has not been reported (Forro, 1987), and algal proteins have been reported to have a low digestibility (Michel et al., 1996). This may be due to their cellular localisation or their putative associations with cell wall polysaccharides (Kloareg and Quatrano, 1988). Presence of polyphenols and salt (Ghosh et al., 1981) reduces the biodegradability of algae. For most algae, aspartic and glutamic acids constitute together a large part of the amino acid fraction (Fleurance, 1999). Degradation of cellulose is catalysed by cellulases and occurs both under aerobic and anaerobic conditions. A combined enzymatic attack of agarases, alginate lyases, proteases and cellulases may be necessary to degrade the algal cell wall, as seen in the case of protoplast isolation (Butler et al., 1989).

### 3.3. MICROALGAE FOR BIODIESEL

Microalgae appear to be one of the important sources to capture solar energy as they are sunlight-driven cell factories that convert carbon dioxide to potential biofuel, food, feeds and high bioactive compounds (Metting and Pyne, 1986; Spolaore et al., 2006). Some species of microalgae contain much higher percentage of oil than conventional oil crops (Table 3). Microalgae can duplicate their biomass in less than 7 days, whereas higher plants take many months or years (Vinshak et al., 1982). Another advantage of microalgae is that their chemical composition can be manipulated by altering the growth environment of the algal species. Carbon dioxide emitted from combustion processes such as power plant, cement plant, steel plant, etc., can be used as a source of carbon for algal growth (Sahoo et al., 2012). Microalgae can be cultivated in seawater or brackish water, raceway ponds on non-arable land and do not compete for resources with conventional agriculture. Microalgal biomass can be harvested during all seasons. Studies on screening of potential microalgae for biodiesel have been reported (Devi, 2008; Devi et al., 2009), but the actual production of biodiesel from microalgae is only in incipient phase.

### 3.4. PROCESSING OF MICROALGAL BIOMASS FOR BIODIESEL PRODUCTION

The recovery of microalgal biomass requires processes such as dewatering, disruption of the microalgae cells and extraction of the oil fraction. Dewatering mechanisms can be grouped as physical (e.g. centrifugation, spray drying and
filtration), biological (e.g. auto flocculation) or chemical (e.g. alum flocculants). Mechanisms of cell disruption and extraction include grinding, direct solvent extraction, explosive decompression, freeze-drying and supercritical fluids amongst others.

3.4.1. Flocculation
Microalgae are very small so they are very difficult to harvest. Flocculation is the process where the microalgal cells are aggregated in order to increase the particle size. Some flocculating agents such as alum, ferric chloride, ammonium sulphate, ferric sulphate, (Brennan and Owende, 2010) polyacrylamide polymers, (Lee et al., 2009) surfactants, chitosan and other man-made fibres are normally used as flocculating agents (Divakaran and Pillai, 2002).

3.4.2. Filtration
Filtration is another very simple method for harvesting of microalgae. But this method depends largely on the microalgal sizes. During filtration, the pore size of the filter depends on the size of the microalgae and the aggregation rate of microalgae. Culture purity is also important while choosing the filter pore size.

3.4.3. Centrifugation
Centrifugation is also widely used for the harvesting of microalgal biomass. The process is rapid and energy intensive, and biomass recovery depends on the settling characteristics of the cells which are again depending on the density and the radius of the microalgal cells and sedimentation velocity (Brennan and Owende, 2010).
3.4.4. Drying
The harvested microalgal biomass must be processed rapidly for drying. There are various methods for drying which include sun-drying, low-pressure shelf drying, drum drying (Prakash et al., 1997), spray drying (Desmorieux and Decaen, 2006), fluidised bed drying (Leach et al., 1998), freeze-drying (Grima et al., 1994) and Refractance Window™ technology drying (Niindo and Tang, 2007). Sun-drying is the cheapest drying method, but it takes long time to dry, and a large drying surface is required. Spray drying is commonly used for extraction of high value products, but it is relatively expensive and can cause significant deterioration of some algal pigments. Freeze-drying is also an expensive method.

3.4.5. Disruption of Microalgal Biomass
Alternatively to drying, oil can be extracted from wet algal biomass. For this, the algal cells must be broken, or lysed, to extract the oil. Some of the disruption methods for cell rupture include osmotic shock, explosive decompression, mechanical press and mechanical and biological shear. Interestingly, some microalgae degrade through the shearing action of the pumps used in bioreactors, so mechanical shear may also be an option (Shields et al., 2008).

3.4.6. Oil Extraction
Once the cell is ruptured, the lipid fraction, consisting of fatty acids and glycerol, needs to be separated from the remaining cell contents. This can be done by solvent or some other extraction process. Biodiesel is then produced by transesterification in which triglycerides are reacted with methanol to yield glycerol and methyl esters of fatty acids (Mata et al., 2010).

4. Algal Biorefinery for Biofuel Production

According to International Energy Agency (2008), “biorefining is a sustainable processing of biomass into a spectrum of marketable products and energy such as biofuel”. A biorefinery is a network of facilities that integrates biomass conversion processes and equipment to produce transportation biofuels, power and chemicals from biomass. This concept is analogous to today’s petroleum refinery, which produces multiple fuels and products from petroleum (Cherubini, 2010).

Production of food and fuel is complexly adjoined. Sustainable production of food and fuel is crucial in a carbon-smart society. Integration of the emerging biorefinery concept with other industries in many environmental deliverables while mitigating several sustainability-related issues with respect to greenhouse gas emissions, fossil fuel usage and land use changes for fuel production and future food insufficiency (Subhadra and Grinson-George, 2011).

Production of biofuel from both micro and macro algae is capital intensive energy consuming which involves various chemical and physical processes. Therefore, production of only biofuels from algal biomass will not be cost-effective and environment friendly. Therefore, it is important to produce biofuel
as co-products along with other by-products through an integrated system of biorefinery approach.

The present biorefinery concept (Fig. 8) emphasises large-scale cultivation of algal biomass (both micro- and macroalgae) and their on-site processing for production of biofuel and other co-products. The most important energy products which can be produced in algal biorefineries are liquid biofuels which include bioethanol, biodiesel, etc. The most important biomass products in algal biorefineries are:

- Biomass – health food, functional food, feed additive, aquaculture, biofertiliser
- Phycocolloids – agar, carrageenan, alginates
- Pigments/carotenoids – astaxanthin, phycocyanin, phycoerythrin, fucoxanthin,
- Vitamin – A, B1, B6, B12, C, E, biotin, riboflavin, nicotinic acid, pantothene and folic acid
- Other/pharmaceuticals – antifungal, antimicrobial, antiviral, toxins, amino acids, proteins and sterols
- Antioxidants – β-carotene, tocopherol
- Antioxidant extracts – arachidonic acid (ARA polyunsaturated omega-6 fatty acid, docosahexaenoic acid) (DHA omega-3 fatty acid), PUFA extracts (polyunsaturated fatty acids)

Various products and by-products derived from integrated algal biorefinery can feed various industries such as pharmaceutical and food production sector (Subhadra and Grinson-George, 2011). In addition to the above-mentioned products and by-products, the following benefits are also associated with integrated algal biorefinery:

- Net energy gain
- Fulfilling a large portion of world food demand without affecting current food supply
• Can provide livelihood and employment to millions of people worldwide
• Environmental benefits in the form of carbon sequestration and nutrient recycling
• Minimum use of water, energy and land than other plant
• Prospect of setting up in wide range of water

5. Conclusion

Biofuels derived from oil crops, waste cooking oil and animal fats are carbon neutral alternatives to petroleum fuels. However, they cannot realistically satisfy even a small fraction of the existing demand for transport fuels. Therefore, the future of biofuels will depend on the accelerated diffusion of new technologies, with an appropriate and market-friendly regulatory environment. Biofuels from algae can become one of the alternative options for supplementing the petroleum-based fuel without affecting the human food chain and environment.

6. References


Devi SS (2008) Screening, isolation and laboratory scale culture of microalgae for biodiesel produc...
BIOFUEL PRODUCTION FROM ALGAE


IEABioenergy-Task42


Using algae for carbon dioxide capture and bio-fuel production to combat climate change

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ABSTRACT

The global carbon cycle has altered significantly due to extensive use of fossil fuels, coal etc. This lead to increase in the emission of Green House Gases such as CO$_2$, CH$_4$, NO$_2$ and Fluorocarbon. In order to achieve environmental and economic sustainability, a renewable, carbon neutral fuels are required that are also capable of sequestering atmospheric carbon dioxide. In this both micro and macroalgae appear to be a major source that can sequester high level of CO$_2$ and can replace fossil fuels. Algae use CO$_2$ as well as water and convert them into carbohydrates and other useful products. Algae are used as food, feed, fodder, fertilizers and pharmaceuticals. Microalgae can be extensively used to capture CO$_2$ from power plants, steel, cement, oil, automobiles and many other industries and the resulting algal biomass can be not only used for biofuel production but also for various industrial products. Macroalgae has a huge potential for the production of bioethanol. Besides giving environmental and economic benefit, large scale algae cultivation can create a large number of jobs at different levels in the society.

Keywords: Algae, Biofuel, CO$_2$ sequestration, Fossil fuel, Global warming,

INTRODUCTION

Over the past 200 years, human activities have altered the global carbon cycle significantly. Understanding the consequences of these activities in the coming decades is critical for formulating economic, energy, technology, trade and security policies that will affect the global environment and economy. The altered carbon cycle is mainly caused by increased CO$_2$ emission in the atmosphere due to extensive burning of fossil fuels. Dresselhaus and Thomas (2001) reported that the fossil fuel currently supply most of the world’s energy needs. The use of fossil fuels results in the emission of Greenhouse Gases such as Carbon dioxide (76%), Methane (13%), Nitrous oxide (6%) and Fluorocarbons (5%). Out of these gases carbon dioxide is the major culprit to cause climate change. The level of carbon dioxide in the atmosphere has increased by 31% since 1750 (Fig. 1). More than 50% of the total annual anthropogenic carbon dioxide production is actually accumulated in the atmosphere, the remainder is found in various terrestrial and oceanic sinks (Ritschard 1992). Such an enormous increase in carbon dioxide in the atmosphere will have disastrous environmental consequences such as rise in the earth’s temperature, rise in the sea level, acidification of ocean, melting of glaciers, extreme weather conditions, change in ecosystems, coral reef bleaching etc (IPCC, 2007; Hill and Ralph 2008). Until and unless major changes are made in the way fossil fuels are used to provide energy, CO$_2$ level in the atmosphere will rise (Hoffert et al., 1998 and Berndes et al., 2003). Therefore, the use of fossil fuel is now widely accepted as unsustainable due to depleting resources and the accumulation of Greenhouse gases in the environment. Since the days of industrial revolution, the developed countries have emitted most of the anthropogenic greenhouse gases into the atmosphere. On the other hand the developing countries are the most vulnerable to climate change impacts because they have fewer resources to adapt socially, technologically and financially (UNFCCC 2007).

Fig. 1. Graph showing increase level of CO$_2$ since 1750. (Courtesy Boden et al 2010).
Therefore, in order to achieve environmental and economic sustainability, the future fuel production processes need to be not only renewable but also capable of sequestering atmospheric carbon dioxide (Schenk et al., 2008). So, a shift from fossil fuels to low carbon fuels becomes the highest priority. The most effective ways to reduce CO₂ emission is to improve the energy efficiency of each economic sector and to reduce the cutting of tropical and temperate forest around the world. These methods however may not be able to control CO₂ emissions due to various political and socio-economic barriers, so other more innovative and less well defined CO₂ mitigation measures are required. The most practical of these innovations is to increase CO₂ sinks through photosynthesis including increased carbon storage in standing tree biomass, substitution of fossil fuels with biofuels, increase in soil carbon sequestration and increase in soil primary productivity (Ritschard 1992). Microalgae can be extensively used to capture CO₂ from power plants, steel, cement, oil, automobiles and many other industries and the resulting algal biomass can be not only used for biofuel production but also for various industrial products. Besides giving environmental and economic benefit, large scale algae cultivation can create millions of jobs at different levels of the society.

**CARBON DIOXIDE CAPTURE BY MICROALGAE**

Amongst various CO₂ sequestration technologies, the biological methods particularly the ones using microalgae, have several merits. These include, direct CO₂ capture and fixation from flue gases by suitable microalgal strains and their biomass conversion into useful products. The last advantage is quite important because the separation of CO₂ from flue gases takes a major portion over 70% of the total sequestration cost (Lee and Lee, 2003). In addition to these advantages, carbon fixed by microalgae is incorporated into carbohydrates and lipids, so that energy, chemicals or food can be produced from algal biomass (Sawayama et al., 1999; Lee et al., 2001; Becker 1994; Metzger and Largeau 1999 and Olaizola 2003). Due to these advantages microalgae can be extensively used to capture CO₂ from power, steel and cement plants as well as transport vehicles exhaust. Much work has been done in capturing CO₂ from power plants (Table1). Various microalgal species including Chlorella kessleri, Chlorella sp. T-1, Chlorella KR-1, Chlorella emersonii, Chlorella HA-1, Chlorella ZY-1, Chlorococum littorale, Synechococcus PCC7942, Stichococcus bacillaris, Thermosynechococcus sp. CL-1, Nannochloropsis oculata, Galdieria partita, Chlorogloeopsis sp., Spirulina platensis etc. (Kurano et al., 1995; Maeda et al., 1995; Yanagi et al., 1995; Kajiwara et al., 1997; Iwasaki et al., 1998; Sung et al., 1999; Yue and Chen 2005; Morais and Costa 2007a; Morais and Costa 2007b; Ono and Cuello 2007; Hsueh et al, 2009; Douskova et al, 2009; Ramanan et al, 2010 and Borkenstein 2011) can be used to capture carbon dioxide from power plants. Various algal strains treated with different concentration of carbon dioxide were also tested (Fig. 2A-B) (Elangbam and Sahoo 2009).

<table>
<thead>
<tr>
<th>Microalgae</th>
<th>CO₂ %</th>
<th>NOₓ ppm</th>
<th>SOₓ ppm</th>
<th>Growth rate in linear phase g L⁻¹ day⁻¹</th>
</tr>
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<tbody>
<tr>
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<td>70</td>
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<td>30</td>
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<td>100*</td>
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<tr>
<td>Chlorella KR-1</td>
<td>30</td>
<td>100</td>
<td>100</td>
<td>0.78</td>
</tr>
</tbody>
</table>

* NOₓ and SOₓ concentration in aqueous phase

(Table1. Growth characteristics of microalgal candidates for biofixation of carbon dioxide (courtesy Lee and Lee 2003)
CARBON DIOXIDE CAPTURE BY MACROALGAE

Macro marine algae popularly known as seaweeds have emerged as a major group for CO₂ sequestration from the ocean. According to Beardall and Raven (2004) marine photosynthesis contributes 54–59 Pg C year⁻¹ of the total primary productivity of planet and out of this ~ 1 Pg C year⁻¹ is contributed by seaweeds and seagrasses. Marine macroalgae such as *Macrocystis*, *Laminaria*, *Sargassum*, *Ascophyllum*, *Fucus*, *Porphyra*, *Palmaria*, *Ulva* and *Enteromorpha* also achieve high rates of CO₂ assimilation per gram fresh weight (Jackson 1987; Gao and McKinley 1994; Muraoka 2004 and Chung et al., 2011). Macroalgae can incorporate an average of 0.26 x 10⁶ tonnes C into the harvested algae annually (Chung et al., 2011) thus, seaweeds also have a good potential in capturing carbon.

ALTERNATIVE FUEL

The escalating price of petroleum and most significantly the emerging concern about global warming which is associated with the burning of fossil fuels has led scientists all over the world to look for an alternative eco-friendly source of fuel. Thus, biofuel has become more attractive because of its environmental benefits as it is made from renewable biological resources. It is biodegradable, non toxic and has low emission profiles, therefore beneficial to the environment.

One hundred years ago, Rudolf Diesel tested vegetable oil as fuel for his car engine. In 1930s and 1940s vegetable oils were used as biodiesel only in emergency situations. Recently increase in crude oil prices coupled with environmental concerns, has resulted renewed interests in production of biofuel. Continued and increasing use of petroleum will intensify local air pollution and magnify the global warming problems caused by carbon dioxide (Shay 1993 and Ma and Hanna 1999). Thus, biofuel has the potential to reduce the level of pollutants and the level of probable carcinogens (Krawezyl 1996 and Ma and Hanna 1999).

Considerable amount of food crops and their products which include maize, sugarcane, wheat, palm oil, soybean, sunflower oil, rapeseed oil etc are being used for production of first generation biofuels. Unfortunately biofuel derived from food crops, edible oil, waste cooking oil and other vegetable oils cannot realistically satisfy even a small fraction of the existing demand for transport fuels (Chisti 2007).

Moreover, biofuels from food crops also contribute to land clearing if they are produced on existing cropland or on newly cleared lands (Buchanan et al., 2008; Curran et al., 2004; Fargione et al., 2008; Nepstad et al., 2008). FAO, 2008 reports concluded that rapid expansion in liquid biofuel production offers both risks and opportunities for the global food and agriculture system primarily through its impact on commodity prices. The immediate risk is that higher prices hurt poor consumers in the developing world, who often spend more than half of their total household income on food (FAO 2008 and Raney 2009). Therefore, it is necessary to minimize environmental risks associated with the first generation biofuels and maximize the potential opportunities for agricultural development that would require a shift away from current policies that subsidize the production of first generation liquid biofuels, towards a more balanced package of policies that consider environmental, food security, energy and agricultural needs in a more integrated way (Raney 2009).

**Algae for biofuel production**

Microalgae can use water and carbondioxide to produce biofuels, food, feeds and high value bioactive compounds. Algae have several advantages over other crops including *Jatropha* (Sahoo 2010). It was already
reported that Microalgae produce 15 – 300 times more oil than the other first generation oil crops (Chisti 2007 and Schenk et al., 2008). Microalgae oil differs from most vegetable oils in being quite rich in polyunsaturated fatty acids with four or more double bonds (Belarbi et al., 2000 and Chisti 2007). The advantage of microalgae over land plants as a source of transportation biofuels are as follows:

- Oil yield per area of microalgal cultures could greatly exceed the yield of the best oilseed crops.
- Microalgae grow in an aquatic medium, but need less water than terrestrial crops.
- Microalgae can be cultivated in sea water or brackish water on non arable land and do not compete for resources with conventional agriculture.
- Microalgae biomass production may be combined with direct biofixation of waste carbon dioxide.
- Algae cultivation does not need herbicides or pesticides.
- The residual algal biomass after oil extraction may be used as feed, fertilizer or fermented to process ethanol or methane.
- The biochemical composition of the algal biomass can be modulated by varying growth conditions and the oil content can be highly enhanced.

Microalgae for biodiesel production

Microalgae contribute a major role as alternative fuels in order to combat global warming due to their high lipid content. One of the most advantages of microalgae is that, their chemical composition can be manipulated by altering the growth environment of the algae of interest. Moreover their chemical composition is influenced by the growth phase and by various environmental factors such as temperature, light etc. thus the key challenges for biodiesel production from microalgae lies in screening and isolation of microalgal strains with high growth rate and high oil content. Screening and isolation using techniques such as filtration, differential centrifugation, micropipetting, serial dilution and agar streaking are the main steps in culture methods for microalgae. Various works were done on screening and isolation of potential microalgae for biodiesel production (Devi 2008 and Devi et al., 2009). Microalgae when grown under nitrogen deficient culture medium and heterotrophic culture medium show a great increase in oil quantity.

CULTIVATION AND HARVESTING

Microalgae can be grown either in open culture systems or closed systems (photobioreactors). Earlier microalgae were grown mainly in open ponds especially for food and feed supplements, waste water treatments, pharmaceuticals, biosorption of heavy metals etc. Closed system of algae cultivation has attracted much interest because they allow a better control of cultivation condition than open systems. In closed photobioreactors higher biomass productivities are obtained and contamination can be easily prevented (Ugwa et al., 2008).

Open Ponds

Open ponds were extensively used in the past for the cultivation of algae (Ugwa et al., 2008; Hase et al., 2000; Boussiba et al., 1988 and Tredici and Materassi 1992). Open ponds can be categorized into natural waters (lakes, lagoons, ponds) and artificial ponds. The most commonly used system includes shallow big ponds, tanks, circular ponds and raceway ponds. Among the types of open ponds, raceway ponds are very common and they have been used for the mass culture of algae since 1950s. The advantage of open ponds is that they are easier to construct and operate, easy to clean after cultivation. However, major limitation in open ponds include poor light utilization by the cells, high evaporation rate, diffusion of carbon dioxide to the atmosphere, requirement of large land areas and prone to contamination which result in low biomass productivity.

Closed System

In order to overcome the limitations of open culture systems, attention is now given on the development of closed culture system. Till now various types of closed system has been developed such as flat – plate photobioreactor, tubular, vertical column etc. In closed system biomass productivities are high and contamination rate are very less compared to open system. Most photobioreactors are characterized by largely exposed illumination surfaces. Closed photobioreactors are good for the immobilization of algae and biomass productivities are very high compared to the open system of cultivation. Closed culture microalgae were also done in the laboratory of Department of Delhi, University of Delhi (Fig.2C-D).
Harvesting of Algae

There is not a particular method for the harvest of algae. The most common harvesting method is flocculation, micro screening and centrifugation. Harvesting process also depends on the type of strain that is cultivated. For example, *Spirulina* sp. is easily harvested by microscreening method. In laboratory filtration is also used but they cannot be applied in large scale cultivation. Flocculation methods are mainly used for the harvesting of algae in raceway ponds (Schenk *et al.*, 2008).

SEAWEEDS FOR BIOETHANOL PRODUCTION

Brown Seaweed contains two main sugars, mannitol and laminarin. Both are easy to extract and are by-products of the alginate industry. Through conversion and fermentation Seaweeds polysaccharides are converted into alcohol. Seaweed doesn't need soil and fresh water as other agricultural biofuel producer crops desperately do. Many criticize that the cultivation of massive agricultural crops to produce bio fuel requires very large acres of land, that makes it inefficient and potentially harm the environment. Food price will rise as the effect of more land is taken away to produce biofuel. Algae / Seaweed grow 10 times faster than sugar cane. According to researchers at the Center for Biorefining of the University of Minnesota and Chisti (2007) reported that Algae / Seaweed produce 5000 gallons (approx 18927 Liters) of bio fuel per acre as compared to the corn which yields 18 gallons (approx 68 Liters), soybeans produce 48 gallons (approx 181 Liters).

CONCLUSION

Most of the World’s energy supply comes from fossil fuel as a result there is rise in the atmospheric CO₂ leading to Global Warming. Thus, it is very important to develop new methods for CO₂ sequestration. At the same time, to develop an alternative clean energy sources which do not depend on fossil fuel and which have a tolerable environmental impact. Therefore carbon sequestration and biofuel production from micro and macro algae becomes one of the alternative to combat climate change as higher plants have various limitations to be used as a model system for carbon sequestration and biofuel production. Numerous work have been done on carbon sequestration and biofuel production by algae but still it needs much research in order to meet the increasing demand for energy. We hope that in future it will replace the fossil fuel to larger extent and reduce the atmospheric CO₂ to combat Global warming.

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