Current Status and Challenges of Microalgae as an Eco-Friendly Biofuel Feedstock: A Review

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Abstract: Global warming, depleting energy reserve and raising demand have created a surge for alternative and environmentally friendly renewable energy sources. Currently, microalgae have recognized as a promising biofuel feedstock's due to the several unique characteristics includes high productivity, no competition for arable land, fresh water and high CO₂ sequestration efficiency. High caloric value, low density and low viscosity make it promising source of renewable energy. They also serve the dual purpose of biofuel production along with the production of potentially valuable biomass, which could be utilize for phyco-remediation, food, animal feeds, fertilizers, drugs etc. In spite of huge opportunity, only few algae species were investigated till date. This review paper presents the brief view on the potential of microalgae for biofuel feedstock, different culturing system, algal conversion technology. In addition, hurdles in commercialization of algal based biofuel technology and strategies were also discussed.

1. Introduction

Continuous rising population and intensive use of fossil fuel brings them close to the point of exhaustion. In addition, combustion of fossil fuel generates green house gases includes carbon dioxides and methane which are the major contributor for global warming and produces sulfuric, carbonic nitric acid and radioactive compounds that adversely affect the environment and human being. Declined energy reserve and increasing fuel demand leads to the search of environmental friendly and sustainable energy sources. Numbers of measures has been taken by the researchers, scientists and by the government for gradual replacement of fossil fuels by the renewable energy sources for sustainable development with same levels of performance. Many alternative sources of energy have been studied and implemented such as solar, energy, hydroelectricity, geothermal, wind, and ocean energy. Each options has own advantages and problems, after being implemented with different degree of success. Recently biofuel has been recognized as an ideal recyclable primary energy source that has the capacity to replace the fossil fuels and to provide economical and social benefits to the society (Mata et al., 2010; Kiran, 2013). Biofuel is a biodegradable, nontoxic and renewable source of energy that could be substantially supplied for long time. It is an environmental friendly
fuel that contributes lower emission of green house gases (GHGs) and aromatic compounds. The primary feedstock’s (includes waste cooking oil, oil crops, animal fat) and secondary feedstock’s (includes terrestrial plants, forest residues) were found as non ideal feedstock for replacement of traditional energy source due to several limitations. Currently, microalgae have attracted the interest for commercial production of biofuel and to replace fossil fuels due to their higher growth rates and higher biomass productivity (Williams et al., 2010). Microalgae are unicellular photosynthetic microalgae utilizes sunlight, and carbon dioxide for its growth and production of valuable components. Compared to primary and secondary feedstock’s they does not compete for arable land, fresh water and food supply. The most advantageous features are its renewability and environmental sustainability (Hosasain et al., 2010). In addition, they have high caloric value, low density and low viscosity. These properties make microalgae more suitable for biofuel production. Despite of several advantages, there are still many challenges in the development of algal derived biofuels, largely associated with cost of production and processing. These limitations can be overcome by adopting the improved harvesting technology and conducting the extensive research for increasing their growth rate and lipid productivity. This review paper presents the brief view on the potential of microalgae for biofuel feedstock, different culturing system, algal conversion technology. In addition, hurdles in commercialization of algal based biofuel technology and strategies.

2. Microalgae as biofuel Feedstock

Over the last 30 years, globally energy consumption have been increased by 49% and would get exhausted in 50-70 years. In order to meet the energy crisis, there is need to focus on alternative sustainable energy sources. Recently, biofuel are identified as most promising environmental friendly feedstock’s to replace fossil fuel. First generation of biofuels are produced from oil seeds including rapeseed oil, palm oil and animal fats and agricultural crops which are rich starch such as sugarcane, sugar beet, maize, using conventional technology (FAO 2008). Since these are used for human consumptions, it can lead to increases competition for arable land, nutrients and freshwater with other edible crops. Therefore, it may produce a negative impact on food security and global food market. To overcome these problems non edible oils, lignocelluloses biomass, forest residues and woody part of plants have been used in second generation of biofuels (Moore 2008). The use of terrestrial plants for biofuel generation requires large cultivation areas, longer time to grow and may lead to arable land competition, biodiversity loss. In addition, commercial production of bio-fuel from first and second generation requires sophisticated and expensive technology. Finally, first and second generation of biofuel are not successful way for sustainable and environmental friendly replacement of conventional fuel as they do compete with other food crops, affects the food security and lead ecological imbalance (Antolin et al., 2002). Recently, microalgae have been proposed as an excellent source of biofuel feedstock. Microalgae are microscopic photoautotrophic which requires sunlight to convert inorganic carbon source into bio-fuels and their valuable biomass. They are more efficient in accessing water, nutrient, and sequestration of CO₂ and have wide range of tolerance for seasonal variation such as temperatures, salinities, pH values; and different light intensities. Table 1 elicited the potential of microalgae over other feedstock’s for biodiesel production.
Biodiesel produced from microalgae is considered as third generation of bio-fuel and possesses several advantages over other generation such as

- Microalgae have higher growth rate, varies from few minutes to few hours which is more than 50 times higher than most of fastest conventional terrestrial crops (Chisti 2007; Mata et al., 2009)
- They have high oil content in the range of 20–50% of dry weight of biomass, which can be 80% in some species.
- They exhibit higher lipid productivity approximately 50-250 times than terrestrial plants.
- Microalgae do not compete with agricultural crops and forestry for arable land and fresh water (Searchinger et al. 2008) as they can grow in non-arable land, brackish water or marine water.
- Microalgae have highly efficient photosynthetic apparatus and convert 8%-10% light to biomass, resulting 77 g/biomass/m²/day.
- They have 20-50% times higher CO₂ sequestration efficiency than terrestrial plants. Therefore, microalgae represent an economical way to fix the waste CO₂. CO₂ mitigation rate is 50.1 ± 6.5% to 82.3 ± 12.5% for different algal species.
- Unlike petroleum based fuels, it is a clean fuel and have very low levels of sulfur emission.
- Cultivation of microalgae do not required fertilizers and pesticides and therefore safe for environment.
- Growth of microalgae can be coupled with water remediation due to its good efficiency to remove inorganic matters from waste water.
- After oil extraction, residual biomass may be used as nutraceuticals, feeds, fertilizers and food industries.

Table 1. Microalgae as biodiesel feedstock (Mata et al., 2010)

<table>
<thead>
<tr>
<th>Plant source</th>
<th>Oil content (% oil by wt in biomass)</th>
<th>OilYield (L oil/ha year)</th>
<th>Water Footprint (m²/ton)</th>
<th>Land use (m² year/kg biodiesel)</th>
<th>Biodiesel Productivity (kg/hector year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize (Zea mays L)</td>
<td>44</td>
<td>172</td>
<td>--</td>
<td>66</td>
<td>152</td>
</tr>
<tr>
<td>Hemp (Cannabis sativa L.)</td>
<td>33</td>
<td>363</td>
<td>--</td>
<td>31</td>
<td>321</td>
</tr>
<tr>
<td>Soyabean (Glycine max L.)</td>
<td>18</td>
<td>636</td>
<td>4200</td>
<td>18</td>
<td>562</td>
</tr>
<tr>
<td>Jatropha (Jatropha curcas L.)</td>
<td>28</td>
<td>741</td>
<td>--</td>
<td>15</td>
<td>656</td>
</tr>
<tr>
<td>Canola/Rapeseed (Brassica napus L.)</td>
<td>41</td>
<td>974</td>
<td>4300</td>
<td>12</td>
<td>862</td>
</tr>
<tr>
<td>Sunflower (Helianthus annuus L.)</td>
<td>40</td>
<td>1070</td>
<td>6800</td>
<td>11</td>
<td>946</td>
</tr>
<tr>
<td>Caster (Ricinus communis)</td>
<td>48</td>
<td>1307</td>
<td>24700</td>
<td>9</td>
<td>1156</td>
</tr>
<tr>
<td>Palm oil (Elaeis guineensis)</td>
<td>36</td>
<td>5366</td>
<td>5000</td>
<td>2</td>
<td>4747</td>
</tr>
<tr>
<td>Microalgae (low oil content)</td>
<td>30</td>
<td>58700</td>
<td>--</td>
<td>0.2</td>
<td>51927</td>
</tr>
<tr>
<td>Microalgae (medium oil content)</td>
<td>50</td>
<td>97800</td>
<td>591-3276</td>
<td>0.1</td>
<td>86515</td>
</tr>
<tr>
<td>Microalgae (high oil content)</td>
<td>70</td>
<td>136900</td>
<td>--</td>
<td>0.1</td>
<td>121104</td>
</tr>
</tbody>
</table>
3. Algal biofuels conversion technologies

After obtaining the dried algal biomass, oil was extracted and converted into biofuel by various methods as illustrated in figure 1.

3.1. Compound extraction

Various physical and chemical methods are used for extraction of lipid from the dried algal biomass. The various physical means such homogenization, bead milling, sonication were employed for disruption of cell structure and releasing lipids in to the solvent mixture (Mata et al., 2010). The most popular and commonly used chemical extraction technique is solvent method. Hexane is mostly common solvent requires significant energy input and toxic. Other techniques include expeller presses, electromagnetic methods, direct liquid fraction, Soxhlet extraction, supercritical fluids (CO$_2$), ultrasonic waves, and microwave-assisted organic solvent extraction have been investigated (Rawat et al., 2016). After extraction of lipid remaining biomass are can be potentially utilized in animal feeds, fertilizers and in nutraceutical industries.

3.2. Main biofuel products

The key process involve in conversion of algal biomass to renewable biofuels are thermochemical, and biochemical process. Thermo-chemical conversion process can be categorized into combustion, gasification, liquefaction and pyrolysis. Biochemical conversion is the energy conversion of biomass via anaerobic digestion and alcoholic fermentation (Spolaore et al., 2006) and chemical conversion lead to the formation of biodiesel via trans-esterification. Main biofuel products from algae are listed below:

3.2.1 Biodiesel

Biodiesel is renewable, non toxic, biodegradable fuels and can replace traditional diesel with little or no engine modification (Demirbas et al., 2011). Biodiesel is the liquid fuel produced from algal oil via trans-esterification. In this process triglycerides converted into fatty acid alkyl esters in the presence of homogenous or heterogeneous catalyst via multiple steps (Ejikeme et al., 2010). The overall trans-esterification reaction

<table>
<thead>
<tr>
<th>Features</th>
<th>Diesel</th>
<th>Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 15 C (Kg/m$^3$)</td>
<td>835</td>
<td>870-890</td>
</tr>
<tr>
<td>Viscosity at 40C (mm$^2$/s)</td>
<td>2-3.5</td>
<td>3.5-6.2</td>
</tr>
<tr>
<td>Sulfur, ppm</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>Carbon %</td>
<td>87</td>
<td>77</td>
</tr>
<tr>
<td>Hydrogen %</td>
<td>13</td>
<td>123</td>
</tr>
<tr>
<td>Oxygen %</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td>Flash Point (c)</td>
<td>60-80</td>
<td>100-117</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>40-50</td>
<td>58-65</td>
</tr>
<tr>
<td>Lower calorific Value MJ/kg</td>
<td>42.59</td>
<td>37.24</td>
</tr>
<tr>
<td>Acid number (mgKOH/g)</td>
<td>Max 0.5</td>
<td>0.37</td>
</tr>
<tr>
<td>Heating value (MJ/kg)</td>
<td>41</td>
<td>40-45</td>
</tr>
</tbody>
</table>
is described in Fig. 3 where the radicals R1, R2, R3 represent long chain hydrocarbons, known as fatty acids. It is environmental friendly and sustainable fuel which gives more clean combustion than petroleum diesel. Biodiesel produces less CO (50%), CO$_2$ (78%), hydrocarbon, SO$_2$, aromatic hydrocarbons, and particulates matter that affects the environment and human health (Chisti 2007). Algal biodiesel contain calorific value 39-41 MJ/Kg close to petrodiesel 46 MJ/Kg (Demirbas, 2010). Table 2 illustrated the comparison of different properties of diesel and biodiesel. Regarding many features biodiesel better than petrodiesel, although main limitation associated with biodiesel its high viscosity. Viscosity is about 10–20 times more than diesel fuel which leads in problem in combustion and leave deposits on the fuel injector of diesel engines. Therefore, biodiesel is usually blended with conventional diesel.

3.2.2 Bio-oil

Algal biomass converted into bio-oil through biochemical process and thermo-chemical process. In thermo-chemical process, whole biomass converted into biogas while in biochemical process specific component (protein, carbohydrate) are converted into bio-oil.

3.2.3 Bioethanol:

Algal biomass rich in carbohydrate converted into bioethanol via fermentation. Microalgae are highly efficient to produce ethanol because unlike first and second generation bioethanol feedstock it does not require chemical and enzymatic pretreatment as not contain lignin and hemicellulose however, mechanical treatments are required to break the cell wall and release carbohydrate (FAO, 2010). It has been found deoiled-algal biomass have 60% higher ethanol conversion efficiency and in addition the extracted oil can use to produce biodiesel. During fermentation, starches, or sucrose hydrolyzed into glucose and fructose in the presence of invertase enzyme then glucose and fructose forms ethanol in presence of zymase enzyme or yeast such as Saccharomyces cerevisiae (Harun et al, 2010).The overall reaction for ethanol production from biomass is:

$$C_6H_{12}O_6 + 2ADP+2Pi-2C_2H_5OH+2CO_2+2ATP+2H_2O$$

3.2.4 Biomethane

Anaerobic digestion of carbohydrate by anaerobic microorganisms produces biogas which is the mixture of methane (55–75%) and CO$_2$ (25–45%) and also be converted to generate electricity. Dębowski et al (2013) reviewed the effectiveness of biogas production with the use of macroalgae as a substrate and found to produce 73% of methane. Microalgae are suitable substrate for biogas production due to its low lignin and high bio-components which can further be reprocessed to make fertilizers. Lipid extracted microalgal biomass is rich in protein and carbohydrate and considered as primary substrate for biogas production. Although, use of microalgae for commercial production of biogas are still in their very early state and further research in this field.

3.2.5 Biohydrogen

Different microalgal strains also have driven the interest for production of biohydrogen via photofermentation and dark fermentative process using mixed culture (Enzing et al 2014). It has the highest energy density (122 kJ/g) in comparison with other fuels. Biohydrogen is carbon free fuel which can be generated via gasification and photolysis.
It is a clean fuel and can maintain long term engine efficiency. The main obstacle in the way of commercialization of biohydrogen production is cost of hug photobioreactor and hydrogen storage devices (Cheng and Timilsina, 2011; Demirbas 2011).

**Figure 1**- Process of biofuel production from microalgae

### 4. Limitations and strategies of biofuel production from microalgae

The high growth rates, higher lipid productivity and positive environmental effects seek the interest of researcher and scientist to turn algae into bio-fuels. However, cost of production and processing is one of the major hurdles in adopting microalgae as biofuel feedstock (Demirbas, 2011). The study of Gouveia (2011) indicated that many times industry is holding the results regarding on production and processing costs and therefore there is lack of data on public domain. According to the result of Richardson et al. (2012) study, the estimated production cost of microalgae in raceway ponds and photobioreactors are US$ 3.80 and US$ 2.95 per kg, respectively. This indicated that bioalgal production is more economical in open pond than PBR. The cost of production of algal biofuel is calculated by estimating the individual cost of various contributors such as cost of land, equipment, labor, nutrients supply, water supply, power consumption, and tax. Although, estimating the cost of these variables is not easy, thus cost per kg of dry algae biomass is calculated as an alternative measure. Depending on the processes and procedures used, the cost per liter of oil were varied in different studies. It have been found that 1 l of algal biofuel cultivated in photobioreactor with 30% oil content, would cost US$ 2.8 while palm oil having 35% oil content would cost US$ 0.66 and 1 l of petrodiesel would cost US$ 0.49, which is far from being economically feasible. Extensive efforts have been implemented by several agencies and companies for commercial viability for algal based biofuel technologies. Biomass productivity of 2g.L-1day-1 with lipid content of 20% DW would cost US$ 130 per barrel crude oil which is considering the viable limit. In order to achieve commercial feasibility, microalgal production cost must be 1 USD L-1 which would be competitive with production costs for biofuels from conventional energy crops ranged from 0.21 to 0.99 USD L-1 (Park et al., 2016). The economics feasibility of algal biofuel production could be greatly improved through
increasing productivities, lowering costs or development of additional income streams. It includes following criteria:

4.1 Selection of algal strain

There is broad opportunity to produce wide range of biofuels such biodiesel, bioethanol, biogas from algal biomass. Selection for the best algal species is the primary strategy for production of algal-biofuel technologies which depends on high productivity. The carbohydrate and/or lipid rich algal biomass were preferred for the production of most promising biofuel includes bioethanol and biodiesel. Commercial productions of bioethanol are limited due to low carbohydrate content in algal biomass while intensive researches have been conducting for biodiesel production. The selection of oleaginous microalgal strains for biodiesel production is focused on lipid content and FA composition however, production of carbohydrates, lipids, and other compounds of interest can be increased in stress conditions such as limitation of nutrients, light intensity, salinity, pH. Gong & Jiang (2011) advocated that ease of harvesting, ability to withstand in extreme condition and production of by-products is also important criteria to reduce the cost of the substrate. The most common algal have been studies for biofuel feedstock are Botryococcus braunii (50–80%), Chlorella (18–57%), Dunaliella primolecta (23%), Nannochloropsis sp. (31–68%) (Chisti 2007).

4.2 Adaptation of efficient cultivation system

Microalgae are cultivated either in open pods or photobioreactors. Each system has own advantage and limitations as discussed earlier. Till now, either of design was found ideal and further research needed to redesign cultivation system for optimized production in terms of cost, productivity and energy.

4.3 Reducing the need of fresh water

It is feasible to cultivate microalgae in waste water and marine water and reduced the need and cost for freshwater. Utilization of marine water for commercial algae cultivation has recently attracted the interest, although it limited to marine microalgae. Microalgae utilize nutrients present in sea water and sea waves’ gives agitation for mixing and thereby increase biomass productivity. This approach has good potential for reducing the cost of production as it reduces the cost of freshwater, nutrients and mixing. However, it needs further investigation to find out the challenges and extensive R&D efforts. Several studies have found cultivation of microalgae in waste water as more promising way to get dual advantage of waste water treatment and to reduce both production costs and freshwater requirement (Chinnasamy et al. 2010; Pittman et al. 2011; Sydney et al. 2011). Microalgae effectively remove inorganic compounds such as nitrogen and phosphorus from effluent wastewater and assimilate for biomass production. Yang et al.2012 reported the cultivated of microalgae in seawater and wastewater over freshwater could reduce 90%need of freshwater in open pond systems and further recycling of the harvested water could reduce the water and nutrient requirements by 84% and 55%, respectively.

4.4 Two-stage cultivation strategy

Physiological stresses such as change in light intensity, salinity, pH, nutrient medium alter the biochemical pathways and facilitate the accumulation of nutrient in microalgae. Nutrient deficiency has been found to be the most suitable stimulant to raise lipid
content in number of microalgal species however; it lowers the growth rate and biomass productivity. Chlorella species can accumulate up to 58% lipid under low nitrogen conditions. This difficulty can be overcome by adaptation of two-stage cultivation strategy. In two-stage strategy, the first stage is dedicated for cell growth/division in nutrient-sufficient medium, and the second stage for lipid accumulation under nutrient starvation or other physiological stresses.

4.5 Adaptation of Biorefinery system

Further improvement of economical feasibility of the biofuel production could be attained by adopting the bio refinery system. It is a strategy in which whole biomass were affectively utilized for production of multiple of valuable products. It is a new approach that lowers the overall production costs by simultaneous production of biofuels and high valuable compounds such as antioxidants, fertilizers, from the same batch of biomass without the damage of other fractions (Vanhoor-Koopmans et al; 2013). In this approach, first starch and lipids fractions were extracted for biofuel production and then residual algae cake is rich in proteins and bioactive compounds were utilized in different fields includes pharmaceuticals, human nutrition, animal feed, fertilizers and in cosmetics.

4.6 Harvesting techniques

The major bottleneck of utilization of microalgae as biofuel feedstock is the cost of harvesting technology. The small cell size and lower density (less than1g/l) of microalgae makes harvesting difficult and costly (Danquah et al., 2009). No methods have been considered ideal to harvest all microalgal strains with the same efficiency. Selection of algal stain with high lipid productivity and requires low cost and energy for harvesting. The harvesting efficiencies were based on microalgal properties, such as size, cell morphology, cell surface properties. For example, the cyanobacterium Spirulina is long spiral shape (20–100 mm long) naturally lends itself and easily harvest (Brennan et al.,2010).

4.7 Genetic and metabolic engineering

It is most advanced and modern methods for improvements of algal biology and productivity (Gangl et al.,2015). Currently, there is increasing interest in the genetic manipulation of promising organism that gives higher commercial returns in terms of biofuels and value added products both however, it is still in its infancy.

5. Current status of algal biofuel technology

Over the last few year, biofuel industry have been growing steady and increased sevenfold since 2000. Although commercial production of algal based biofuel is still in their incipient phase and still meets only 2.3% of final liquid fuel demands (Bhatt et al. 2014). Around the world several agengies such as Algenol, Sapphire Energy and Seambiotic etc. are involve in the development of microalage based biofuel production systems. Since 1980s, the National Renewable Energy Laboratory (NREL),one of the pioneer agency has been focus on algal based biodiesel program. Among of millions of algae, over 40 000 species have identified and on which only few were explored for biofuel potential. Microalgae received the considerable interest around the world due to its high lipid productivity and potential for wastewater treatment and atmospheric CO₂ mitigation. They are capable of producing algal oil 58,700 L/hac which can produce
121,104 L/hac biodiesels. At present cost of production of microalgae is higher than plants due to the high cost of production, maintenance, harvesting and conversion (Park and Lee, 2016). Therefore, urgent needs exist to adopt cost effective technological strategies in every step from production to conversion of algal biomass to biofuel and moved the algal production from laboratories to commercial scale. Countries includes Europe, USA, China, Japan are the intensively involve in producing biofuels at the commercial level.

6. Conclusions

Microalgae are most promising alternative of fossil fuel due to its higher productivity, does not compete with arable land and freshwater, capacity to mitigate CO₂ and waste water remediation. Microalgae are also rich in bioactive compounds that can be use in different industry such as pharmaceutical, food industry, animal feeds. This review paper has discussed the potential of different generations of biofuel, suitability of microalgae for biofuel production, different types of cultivation system and algal conversion technologies. Despite of several advantages of microalgae for biofuel production, this technology is in their infancy stage. We have outlook on the associated constraints and strategies to make them feasible and viable for commercialization. Economical feasibility is one of the major hurdles to commercialization of algal based biofuel technology. For the economic sustainability of microalgae as a biofuel feedstock, intensive research and cost-effective technological approaches can be developed.

References


