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Potential of Algae for Biofuel Production

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Abstract

A non-renewable fuel like petroleum has been used from centuries and its usage has kept on increasing day by day. This also contributes to increased production of greenhouse gases contributing towards global issues like global warming. In order to meet environmental and economic sustainability, renewable, carbon neutral transport fuels are necessary. To meet these demands microalgae are one of the key sources for the production of biodiesel. These green microalgae synthesise lipids by using sunlight like plants do but in a much more efficient manner. Biodiesel provides more environmental benefits, and being a renewable resource it has gained lot of attraction. However, the main obstacle for commercialization of biodiesel is its cost and feasibility. Biodiesel is usually used by blending with petro diesel, but it can also be used in pure form. Biodiesel is a sustainable fuel, as it is available throughout the year and can run any engine. It will satisfy the needs of the future generation to come. It will meet the demands of the future generation to come.

Keywords: algae, biofuel production, biodiesel

1. Introduction

A 2010 study published in the journal, Energy Policy by researchers from Oxford University, predicted that demand for crude oil would surpass supply by 2015, unless forced by strong recession pressures caused by reduced supply or government interference. On an average, human utilizes fossil fuels which results in the release of 29 giga tonnes CO each year. This critical situation has led to the emergence of an eco-friendly, alternative fuel like biodiesel. According to United States Environmental Protection Agency, the volume requirement of the biomass based on diesel in 2013 is 1.28 million gallons which accounts for 1.13% of the total renewable fuels. This, combined with growing demand, significantly increases the worldwide prices of petroleum derived products. Most important concerns are the availability and price of liquid fuel for transportation [1-3].

Energy shortage refers to the crisis of energy resources to an economy. There has been a massive uplift in the global demand for energy in recent years as a result of industrial development and population growth. Since the early 2000s, the demand for energy, especially from liquid fuels, and limits on the rate of fuel production have created such a stage leading to the current energy crisis. The cause may be overconsumption, aged infrastructure, choke point disruption or crisis at oil refineries, and port facilities that confine fuel supply.

1.1. Microalgae as a source of biofuel

Microalgae are unicellular and simple multicellular microorganisms, including prokaryotic microalgae that are cyanobacteria (chloroxybacteria) and eukaryotic microalgae for example, green algae (chlorophyta), and diatoms (bacillariophuta). These microalgae are beneficial as they are capable of all year production; they grow in aqueous media and hence need less water than terrestrial crops. Unlike other biodiesel corps microalgae does not require herbicides or pesticides, microalgae also produce beneficial co-products such as proteins and residual biomass after oil extraction, which can be used as feed or fertilizer or can be fermented to produce ethanol or methane; the oil yield, can be significantly increased by varying growth conditions to modulate biochemical composition of algal biomass [4-5].

The algal biofuel technology includes selection of specific species for production and extraction of valuable co-products. Algae are bioengineered for achieving advanced photosynthetic efficiencies through continued development of production system. Challenges include, only single species cultivation techniques which are developed so far and are recommended to follow globally, but mixed culture may yield more algae oil than mono culture. The cost of producing oil from algae is economically cheaper than extracting oil from other sources which includes techniques such as water pumping, CO2 transmission, harvesting and extraction [6-7]. This review focuses on microalgae as a potential source of biodiesel.

1.2. Macroalgae for biofuel production

Other algae like macroalgae are generally fast growing and are able to reach sizes up to 60 m in length. Growth rates of macroalgae far exceed those of terrestrial plants. For example, brown algae biomass of the average productivity was approximately 3.3 to 11.3 kg dry weight m^{-2} yr^{-1} for non-cultured algae and up to 13.1 kg dry weight m^{-2} over 7 month for cultured algae compared with 6.1 to 9.5 kg fresh weight m^{-2} yr^{-1} for sugar cane, a most productive land plant. They are seasonally available in the natural water basins. Cultivation of macroalgae at sea, which does not require arable land and fertilizer, offers a possible solution to the energy crisis. Macroalgal biomass contains high amounts of sugars (at least 50%), which can be used in ethanol fuel production [8].

2. Algal fuel

Algae fuel or algal biofuel is another form of fossil fuel that uses microalgae as its source of natural deposits. Some of the unique characteristics of algal fuels are as follows: they can be grown with negligible impact on fresh water resource, they can be synthesized using ocean and wastewater, and they are biodegradable and relatively harmless to the environment if spilled. Algae cost more per unit mass due to the high capital and production costs. [9]

The US Department of Energy's Aquatic Species Program final report recommended that biodiesel could be the only feasible method to produce enough fuel to change current world diesel consumption. Algal fuel is highly favourable and feasible related to other biofuels, as they do not have to produce structural compounds and they can convert higher fractions of biomass to oil compared to other cultivated crops [10].

Studies display that some species of algae have the ability to produce up to 60% of their dry weight in the form of oil. Because the cells grow in aqueous suspension, where they have more effective access to water, CO_2 and nutrients are capable of producing large amounts of biomass and usable oil in either high rate algal ponds or photo bioreactors.

Figure 1. Advantages of algal fuel

2.1. Macroalgae

Notoya, 2010 says that macroalgae's are the most important component in the marine ecosystems that serve for the marine bioresources preservation by preventing eutrophication and pollution. Macroalgae belong to the lower plants, in that they do not have roots, stems, and leaves. They can grow very fast and in sizes of up to tens of meters in length. Based on their pigmentation, they are classified into Phaeophyta (brown), Rhodophyta (red), and Chlorophyta (green) algae [11]. In their natural environment, macro-algae grow on rocky substrates and form stable, multilayered, perennial vegetation, capturing almost all available photons. Approximately 200 species of macroalgae are used worldwide, about ten of them are intensively cultivated, such as the Phaeophyta, Laminaria japonica and Undaria pinnatifida, the Rhodophyta, Eucheuma, Gracilaria, Porphyra and Kappaphycus, and the Chlorophyta, Enteromorpha and Monostroma [12]. Figure 2 shows examples of some commercially exploited macroalgae.

Advantages of algal biofuel production are shown below:

- Production of biofuel from the macroalgae cultivation in seawater is a new approach, and since macroalgae have a unique life cycle in one productive year more than five harvests can be made.
- Macroalgae can succeed in salty water with only sunlight and available nutrients from the seawater.
- Production of bioethanol has a large impact on the environment in general due to eutrophication, acidification, and ecotoxicity.

- With the advancement of genetic engineering, it is now possible to develop a suitable species of macroalgae for bioethanol production [13]. Genetically engineered macroalgae would need to be cultivated in enclosed bioreactors.

- Converting the macroalgal biomass to ethanol rather than using terrestrial plant biomass have some important benefits, i.e., no negative impact on the food security. The relatively high sugar content and lower lignin content than lignocelluloses facilitates high mass production. [14]

- Apart from bioethanol production, algal biomass can be used for the production of an enormous variety of supplementary products i.e., protein, pigments, plastics, etc. [15]

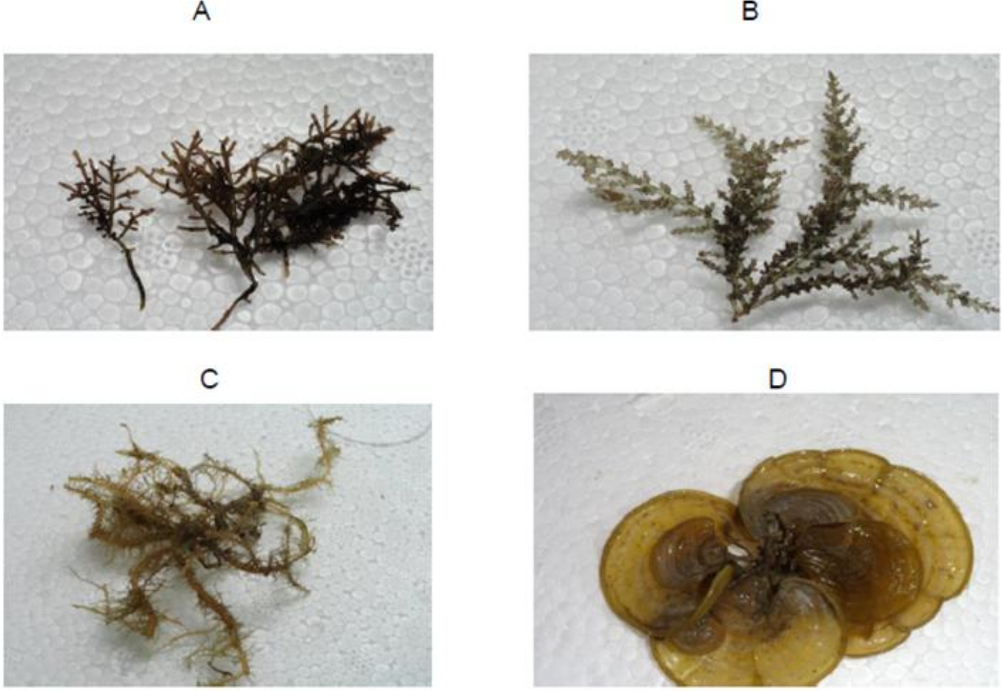

Figure 2. Some commercially exploited macroalgae A) Gracilaria dura B) Acanthophora spicifera C) Hypnea esperi D) Padina pavonica (Rajkumar et al. 2014)

There are some species of macroalgae which gather a high amount of carbohydrates that are capable in the processes of microbial conversion as substrate, i.e., production of biofuels or the other desirable and attractive chemicals with high product price.

Recently it is discovered that triglycerides from a number of macroalgae such as *Ascophyllum nodosum, Codium tomentosum, Enteromorpha intestinalis, Fucus spiralis, Saccorhiza polyschides, Sargassum muticum, Ulva rigida*, and *Pelvetia canaliculata*, etc. could be used to produce biodiesel by a transesterification process. Macroalgae such as Sargassum spp., *Gracilaria spp., Prymnesium parvum, Gelidium amansii,* and *Laminaria spp*. are promising candidates for bioethanol production. [16]

Table 1 Carbohydrate Contents of Macroalgae (Dhargalkar and Pereira 2005)

Species	Carbohydrates (%)
Ulva	42.0
Enteromorpha	64.9
Monostroma	63.9
Laminaria	39.3
Alaria	39.8
Sargassum	33.0
Padina	31.6
Porphyra	45.1
Rhodymenia	44.6
Gracilaria	61.75

2.2. Microalgae

Microalgae are photosynthetic microorganisms that are found in both marine and freshwater habitats. Microalgae species at present, are divided into four groups, namely diatoms (Bacillariophyceae), green algae (Chlorophyceae), blue green algae (Cyanophyceae), and golden algae (Chrysophyceae) [17]. The dominating species of microalgae in commercial production include Isochrysis, Chaetoceros, Chlorella, Arthrospira (Spirulina), and Dunaliella. As heterotrophs, the algae rely on glucose or other utilizable carbon sources for carbon metabolism and energy. The biomolecules such as carbohydrates, proteins, lipids, and nucleic acids are the common constituents in microalgae.

Commercial applications of microalgae have gained interest during the last few years. Owing to their rapid growth rate, i.e., 100 times faster than the land based plants which can double their biomass in less than 1 day, microalgae appear to be an attractive renewable energy source [18]. This is mostly due to their simple cellular system and big surface to quantity ratio that gave them the facility to utilize more amounts of nutrients from the source of water and hence, supporting their algae growth rate.

Biofuel production using microalgal farming offers the following advantages [19]:

- Increased efficiency or decrease in the cost. The sum of harvesting and transportation of microalgae costs can be relatively low compared to those of the other plant biomass resources.
- Generally, microalgae can grow in fresh, brackish, or salt water environments or non-arable lands that are incompatible for growing other crops and conventional agriculture. Microalgae produce a greater yield per hectare with superior environmental attributes.
- The most common microalgae contain oil ranges between 20 and 50% by dry weight of biomass, but superior productivities can be attained. [20]
- Microalgae are able to fix carbon dioxide in the atmosphere, assisting the reduction of atmospheric carbon dioxide levels, which is recently considered a global crisis. In addition, production of microalgal biomass can affect the biofixation of waste carbon dioxide, reducing the releases of a major greenhouse gas (1 kg of dry microalgal biomass requires about 1.8 kg of carbon dioxide). [21]

Table 2 Oil Content of Microalgae by Chisty (2007)

Feedstock	Oil content (% dry wt)
Botryococcus braunii	25-75
Chaetoceros calcitrans CS178	39.8
Nannochloropsis sp.	31-68
Schizochytrium sp.	50-77
Skeletonema sp. CS252	31.8
Tetraselmis suecica	15-23

The green algae *Chlorococum spp*. and *Spirogyra spp*. have been revealed to accumulate high contents of polysaccharides together in their complex cell walls and as starch. This accumulation of starch can be used in the bioethanol production. Bioethanol has the prospect of being an alternative fuel, but it is highly important to ensure that the expansion of this fuel is not hindered by the raw material constraints. In this context, the harvesting cycle of microalgae cells has a very short period (1 to 10 days) compared with the other feedstock (harvesting time once or twice per year), and thus can provide enough supplies to meet demands for the ethanol production. [22]

Table 3 Bioethanol Production from Various Strains of Microalgae

Feedstock	Ethanol yield (g ethanol/g substrate)
Chlorococcum humicola	0.52
Chlorococcum infusionum	0.26
Chlamydomonas reinhardtii	0.24

3. Production

3.1. Algae cultivation

Algae are typically found growing in ponds, waterways, or other wetlands which receive sunlight and CO_2. Growth varies on many factors and can be enhanced for temperature, sunlight utilization, pH control, fluid mechanics, and more. Man-made production of algae tends to replicate the natural environments to achieve ideal growth conditions. Algae production systems can be organized into two distinct categories: open ponds and closed photo bioreactors. Open ponds are simple expanses of water sunken into the ground with some mechanism to deliver CO_2 and nutrients with paddle wheels to mix with the algal broth. Closed photo bioreactors are a broad category referring to systems that are bounded and which allow more precise control over growth conditions and resource management. [23].

3.2. Algae biofilm

Biofilm formed by algae can be harvested easily using unit operations like filtering, scraping, size, reduction, and drying. Photoreactors are used to produce high quality algae in either sessile form or mainly biofilm. Attached algae have produced more oil than planktonic form. The reason for high lipid content is due to alteration in the lipid metabolic pathway of attached algae resulting in change in the membrane fluidity of algae to make them attached to a substratum. For small-scale as well as large-scale production, the photoreactors are used wherein natural or synthetic light can be used to grow algae.

3.3. Algae harvesting and oil extraction

Production of oil from algae is a straight forward process that consisted of growing the algae by providing necessary inputs for photosynthesis, harvesting, dewatering, and oil extraction. Energy in the form of photons is absorbed by the algae cells, which convert the inorganic compounds of CO_2 and water into sugars and oxygen. The sugars are eventually converted into complex carbohydrates, starches, proteins, and lipids within the algae cells. In order to extract the valuable lipids, a series of steps must be undertaken to isolate the algae cells and oil (see Figure 3).

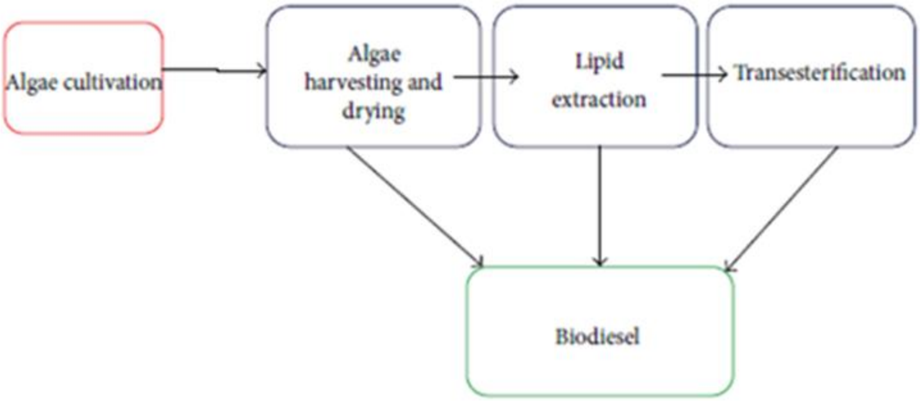

Figure 3. Algae growth and harvesting process

3.4. Trans-esterification

Biodiesel from algae is commonly produced by the transesterification. There are several procedures for carrying out this transesterification reaction including the collective batch process, supercritical processes, ultrasonic methods, and even microwave methods.

Chemically, trans-esterified biodiesel comprises a mix of mono-alkyl esters of long chain fatty acids. The most conjoint form uses methanol (converted to sodium methoxide) to produce methyl esters (commonly referred to as fatty acid methyl ester (FAME) as it is the cheapest alcohol available; though ethanol can be used to form an ethyl ester (commonly referred to as fatty acid ethyl ester (FAEE), biodiesel and higher alcohols such as isopropanol and buthanol have also been used. Using alcohols of higher molecular weights improves the cold flow properties of the resulting ester, at the cost of a less efficient transesterification reaction. A lipid transesterification production process converts the base oil to the desired esters. Any free fatty acids (FFAs) in the base oil are either converted to soap or removed from the process, or they are esterified (yielding more biodiesel) using an acidic catalyst. After this processing, biodiesel has combustion properties very similar to those of petroleum diesel and can be replaced fully or partially for petroleum.

4. Use of algae for biofuel production and waste water treatment

In general, the algal biomass grown with the industrial wastewaters can also be converted into bio crude oil using a thermochemical liquefaction process. Hence, growing algae in wastewaters for biofuel and bioenergy production seems a viable and eco-friendly option for the future. Two main culture systems are available for algal production. An open system generally combines waste treatment with algal production. This system employs the use of ponds, which range from the oxidation ponds to the high rated algae ponds. An oxidation pond recycles nutrients through a bacteria-algae symbiotic process. The pond is one to two meters deep and unmixed. The algal yield in such a pond is thus low. In contrast, the high-rate algae pond (HRAP), which consists of an open raceway mixed by paddle-wheels, is very shallow and is capable of producing very high yields. High-rate algae ponds are suitable for the generation of algal biomass for high-quality animal feed and extraction of useful compounds such as protein and pigments. Research on the combined algal production and waste-treatment systems has been done in Israel, India, Thailand, the United States, and some other countries.

As fresh water sources are scarce, utilization of poor quality wastewaters such as treated municipal sewage wastewater as low-cost nutrient growth medium for mass cultivation of biofuel algae appears a viable option for the future. In recent times, research into microalgal cultivation has gained importance because of application of this resource in the production of biofuels. Cultivation of microalgae in the open pond systems has been used since the 1950, and raceway ponds are the most commonly used artificial systems. Open ponds provide a very efficient method of cultivating algae, but they become contaminated with the algal species very easily.

The major advantage of the open ponds is that they are very easy to construct and operate; in comparison to most closed systems, they are easy to clean up after cultivation and are ideal for mass cultivation of microalgae. This should be given consideration in view of the escalating equipment costs, particularly the use of the reactor-style systems that lack a reliable scale-up method. While considering the economic and the environmental aspects, a raceway pond coupled with a low cost harvesting technique would be a preferable choice to produce biodiesel.

While the demand for the production of biofuel is in part driven by ecological concerns, there is no doubt that constructing and operating an HRAP dedicated to producing algal biomass for biofuels can have an ecological impact. Production of algal biomass using wastewater HRAPs, by contrast, offers a far more interesting proposition from an ecological point of view. The impacts of the HRAP construction and operation are a necessity of providing the treatment of wastewaters and hence, the subsequent algal production represents a biofuel feedstock free of this ecological issue. [24]

Among the various cultivation systems involved in producing algal biomass, the aspect of harvesting biomass is an important economic issue. It was estimated that harvesting algae biomass can account for 20 to 30% of the total production cost. When, the algae grow phototrophically, their concentration is about 0.5 to 1.0 g L-1 for open ponds and around 5 to 10 g L-1 biomass concentration for closed systems. For the production of 1 g L-1 algal biomass, 1000 kg of water must be used to capture 1 kg of biomass. [25]

Methods of algal biomass harvesting, such as filtration, centrifugation, sedimentation and flocculation, and floatation are being practiced either individually or in any combination. Several literature reviews have provided for the algae harvesting techniques. Among the various methods, centrifugation is a possible method suitable for higher-value products but is very expensive in an integrated system producing lower-value products, such as algal oils (http://www.ecs.umass.edu/biofuels). In the case of algal-derived biofuels, the low-cost promising method is gravity settling enhanced by flocculation, without benefit of chemical flocculants. Other mechanisms exist, including the auto flocculation process, and it depends on the coprecipitation of calcium carbonate with microalgal cells and other precipitates that form in hard waters subject to high pH. Apart from settling, in some cases the biomass will float, either due to high oil content or by using a dissolved air flotation (DAF) process.

Employing minor amounts of flocculants to assist in such a process could be cost effective, depending on the amount used. In general, the harvesting method of choice depends on algal species, the cultivation conditions, and the application of the product. For biofuels applications, low-cost algal harvesting techniques are still in process of development. Significant research efforts are needed to develop the cost-effective techniques for harvesting and for production of low cost biofuels from algae. [26]

5. Conclusion

As justified here, microalgal biodiesel is technically feasible. It is the only renewable biodiesel that can potentially and methodically displace liquid fuels obtained from petroleum. Economics of producing microalgal biodiesel need to be improved substantially in order to be competitive with petro diesel, but the level of improvement necessary appears to be possible. Producing low-cost microalgal biodiesel requires primarily improvements to algal biology through genetic and metabolic engineering. Use of the biorefinery concept and advances in photobioreactor engineering will further reduce the cost of production. In view of their much greater productivity than raceways, tubular photobioreactors are likely to be used in producing most of the microalgal biomass required for making biodiesel. Algae biofilm grown in photobioreactors provide a controlled environment that can be tailored to the specific demands of highly productive microalgae to attain a consistently good annual yield of oil.

Nevertheless, diversified biofuels production from algae biomass is very important to improve overall energy balance. For example, higher net value could be achieved by using a combined operation in which algae-produced lipids are converted to diesel fuel and the cellulosic part of the algal biomass (after lipid extraction) is enzymatically converted to glucose, which is fermented to produce bioethanol and other by-products. Apart from that, biofuel contributes to energy security and helps reduce CO2 emissions. A thorough understanding of the past may serve to overcome the past lapses toward building a better future. These recent biofuel discussions demonstrate two issues. First, they show the wide potential utility of these organisms that are capable of producing multiple products ranging from energy, chemicals, and materials to exploitation in the sequestration of carbon and remediation of wastewater. Second, they show the need for energetic support based on factual information to confirm decisions for the strategic improvement of algae and to counter those declarations made on a solely tentative basis to promote commercial investment.

References

[1] N. A. Owen, O. R. Inderwildi, and D. A. King, “The status of conventional world oil reserves—hype or cause for concern?” Energy Policy, vol. 38, no. 8, pp. 4743–4749, 2010.

[2] M. K. Hubbert, Nuclear Energy and the Fossil Fuels. Published in Drilling and Production Practice, American PetroleumInstitute, 1956.

[3] T.Therramus, “Oil Caused Recession, NotWall Street,” January 2010, http://www.oil-price.net/

[4] K. B. Cantrell, T. Ducey, K. S. Ro, and P. G. Hunt, “Livestock waste-to-bioenergy generation opportunities,” Bioresource Technology, vol. 99, no. 17, pp. 7941–7953, 2008.

[5] L. Rodolfi, G. C. Zittelli, N. Bassi et al., “Microalgae for oil: strain selection, induction of lipid synthesis and outdoor mass cultivation in a low-cost photobioreactor,” Biotechnology and Bioengineering, vol. 102, no. 1, pp. 100–112, 2009.

[6] E. Ono and J. L. Cuello, “Feasibility assessment of microalgal carbon dioxide sequestration technology with photobioreactor and solar collector,” Biosystems Engineering, vol. 95, no. 4, pp. 597–606, 2006.

[7] C. U. Ugwu, H. Aoyagi, and H. Uchiyama, “Photobioreactors for mass cultivation of algae,” Bioresource Technology, vol. 99, no. 10, pp. 4021–4028, 2008.

[8] Wi, S. G, Kim, H. J, Mahadevan, S. A, Yang, D., and Bae, H. (2009) “The potential value of the seaweed Ceylon moss (Gelidium amansii) as an alternative bioenergy resource,” Bioresour. Technol. 100, 6658-6660.

[9] “Low Cost Algae Production System Introduced,” Energy-Arizona, August 2007.

[10] T. Shirvani, X. Yan, O. R. Inderwildi, P. P. Edwards, and D. A. King, “Life cycle energy and greenhouse gas analysis for algaederived biodiesel,” Energy & Environmental Science, vol. 4, no. 10, pp. 3773–3778, 2011.

[11] Chan, C. X., Ho, C.L., and Phang, S.M. (2006). “ The trends in seaweed research,” Trends in Plant Science 11, 165-166.

[12] Luning, K., and Pang, S.J. (2003).”Mass cultivation of seaweeds: Current aspects and approaches,” J. Appl. Phycol. 15, 115-119.

[13] Goh, C. S., and Lee, K.T. (2010). “A visionary and conceptual macroalgae-based third generation bioethanol (TGB) biorafinery in Sabah, Malaysia as an underlay for renewable and sustainable development, Renew. Sust. Energy Rev. 14, 842-848.

[14] Adams, J.M., Gallagher, J. A., and Donnison, I. S. (2009). “Fermentation study on Saccharina latissima for bioethanol production considering variable pre-treatments,” J. Appl. Phycol. 21(5), 569-574.

[15] Wijffels, R. (2009). “Microalgae for production of bulk chemicals and biofuels, “The 3rd Congress of Tsukuba 3E Forum, Tsukuba International Conference Centre, Tsukuba, Japan.

[16] Maceiras, R., Rodriguez, M., Cancela, A., Urrejola, S., and Sanchez, A. (2011). Macroalgae: Raw material for biodiesel production,” Appl. Ener. 88, 3318-3323.

[17] Khan, S. A., Rashmi., Hussain M. Z., Prasad, S., and Banerje, U. C. (2009). “Prospects of biodiesel production from microalgae in India,” Renew. Sust. Energy Rev. 13, 2361-2372.

[18] Tredici, M. R. (2010). “Photobiology of microalgae mass cultures: Understanding the tools for the next green revolution,” Biofuels 1,143-162.

[19] Ahmad, A. L., Mat Yasin, N. H., Derek, C. J. C., and Lim, J. K. (2011). “Microalgae as a sustainable energy source for biodiesel production: A review” Renew. Sust. Energy Rev. 15, 584-593.

[20] Mata, T. M., Martins, A. A.m and Caetano, N. S. (2010). “Microalgae for biodiesel production and other applications: A review,” Renew. Sust. En. Rev. 14(1), 217-232.

[21] Rodolfi, L., Zitteli, G. C., Bassi, N., Padovani, G., Biondi, N., and Bonnini, G. (2008). “Microalgae for oil: Strain selection, induction of lipid synthesis and outdoor mass cultivation in a low cost photobioreactor,” Biorechnol. Bioeng. 102(1), 100-112.

[22] Schenk, P. M., Thomas-Hall, S. R., Stephens, E., Marx, U. C., Mussgnug J. H., Posten, C., Kruse, O., and Hankamer, B. (2008). “Second generation biofuels: High-efficiency microalgae for biodiesel production,” Bioener. Res. 1, 20-43.

[23] I. Perner-Nochta and C. Posten, “Simulations of light intensity variation in photobioreactors,” Journal of Biotechnology, vol. 131, no. 3, pp. 276–285, 2007.

[24] Park, J. H., Yoon, J. J., Park, H. D., Kim, Y. J., Lim, D. J., and Kim, S. H. (2011). “Feasibility of biohydrogen production from Gelidium amansii,” Int. J. Hydrogen Energy 36, 13997-14003.

[25] Chisty, Y. (2007). “Biodiesel from microalgae” Biotechnol. Adv. 25, 294-306.

[26] Mutanda, T., Ramesh, D., Karthikeyan, S., Kumari, S., Anandraj, A., and Bux, F. (2011). “Bioprospecting for hyper-lipid producing microalgal strains for sustainable biofuel production,” Bioresour. Technol. 102, 50-57.