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REVIEW ARTICLE

ALGAL BIODIESEL: the next generation biofuel for India

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ABSTRACT

In context of climatic changes and soaring prices per barrel of petroleum, renewable carbon neutral, transport fuels are needed to displace petroleum derived transport fuel, which contribute to global warming and are of limited availability. Biodiesel derived from oil crop is a potential renewable and carbon neutral alternative to petroleum fuel. Unfortunately, biodiesel from oil crop, waste cooking oil and animal fat cannot realistically satisfy even a small fraction of the existing demand for transport fuel. As demonstrated here, biodiesel from microalgae seem to be the most promising renewable biofuel that has the potential to completely displace petroleum-derived transport fuel without adversely affecting supply of food and other crops products. Like plants, microalgae use sunlight to produce oil but they do so more efficiently than crop plants. Oil productivity of many microalgae greatly exceeds the oil productivity of the best producing oil crops. The present review covers the approach for making algal biodiesel more economically and competitive with petrodiesel.

KEYWORDS: *Microalgae, Biodiesel, Transesterification, Tubular Photobiorectors*

INTRODUCTION

Microalgae comprise a vast group of photosynthetic, auto/heterotrophic organism which has an extraordinary potential for cultivation as energy crops. These microscopic algae use photosynthetic process similar to that of higher-developed plants. They are veritable miniature biochemical factories, capable of regulating carbon dioxide (CO_2), just like terrestrial plants [1]. In addition, these micro-organisms are useful in bioremediation applications [2-4] and as nitrogen fixing biofertilizers [5]. This review article discusses the potential of microalgae for sustainably providing biodiesel for the displacement of petroleum derived transport fuels in India.

The need of energy is increasing continuously, because of increase in industrialization as well as human population. The basic sources of this energy are petroleum, natural gas, coal, hydro and nuclear [6]. The major disadvantage of using petroleum based fuel is atmospheric pollution. Petroleum diesel combustion is a major source of greenhouse gases (GHG). Apart from these emissions, petroleum diesel combustion is also major source of other air contaminants including NOx, SOx, CO, particulate matter and volatile organic compounds [7], which are adversely affecting the environment and causing air pollution. These environmental problems can be eliminated by replacing the petroleum diesel fuel with an efficient renewable and sustainable biofuel.

Algal biomass is one of the emerging sources of sustainable energy. The large-scale introduction of biomass could contribute to sustainable development on several fronts, environmentally, socially and economically [8]. The biodiesel generated from biomass is a mixture of mono-alkyl ester, which currently obtained from transesterification of triglycerides and monohydric alcohols produced from various plant and animal oils. But this trend is changing as several companies are attempting to generate large scale algal biomass for commercial production of algal biodiesel.

Biodiesel is non-toxic and biodegradable alternative fuel that is obtained from non-renewable sources. In many countries, biodiesel is produced mainly from soybeans. Other sources of commercial biodiesel include canola oil, animal fat, palm oil, corn oil, waste cooking oil [6, 9, 10]. But the recent research has proved that oil production from microalgae is clearly superior to that of terrestrial plants such as palm, rapeseed, soybeans or jatropha [11, 12]. Important advantage of microalgae is that, unlike other oil crops, they can double their biomass within 24 hr. In fact the biomass doubling time for microalgae during exponential growth can be as short as 3 to 4 hr, which is significantly quicker than the doubling time for oil crops [13]. It is for this reason microalgae are capable of synthesizing more oil per acre than the terrestrial plants which are currently used for the fabrication of biofuels [1] and using microalgae to produce biodiesel will not compromise production of food, fodder and other products derived from crops.

In the production of energy from micro algal biomass, two basic approaches are employed depending on the particular organism and the hydro-carbon which they produce. The first is simply the biological conversion of nutrients into lipids or hydrocarbons. Depending on species, microalgae produce many different kinds of lipids, hydrocarbons and other complex oils [14-16]. The second procedure entails the thermo-chemical liquefaction of algal biomass into lipid or hydrocarbons. Lipids and hydrocarbons can normally be found throughout the micro algal biomass [17]. They occur as membrane components, storage products, metabolites and sources of energy for microalgae. Algal strains, diatoms, and cyanobacteria (categorized collectively as microalgae) have been found to contain proportionally high level of lipid (over 30%). These microalgal strains with high lipid content are of great interest in search for sustainable feedstock for production of biodiesel.

Potential of microalgal Biodiesel

The enormous amount of burning of fossil fuel has increased the CO_2 level in the atmosphere, causing global warming. Biomass is focused as an alternative energy source, as it's a renewable resource and it can fix atmospheric CO_2 through photosynthesis. Among biomass, algae (macro and microalgae) usually have a higher photosynthetic efficiency than other biomass producing plants. Biodiesel from microalgae appears to be a feasible solution to India, for replacing petro-diesel. The estimated annual consumption of petroleum product in India is nearly about 120 million tonnes per year, and no other feedstock except microalgae has the capacity to replace this large volume of oil. To elaborate, it has been calculated that, in order for a crop such as soybean or palm to yield enough oil capable of replacing petro-diesel completely, a very large percentage of current land available need to be utilized only for biodiesel crop production, which is quite infeasible [13]. For small countries, in fact it implies that all land available in the country be dedicated to biodiesel crop production. However, if the feedstock were to be algae, owing to its very high yield of oil per acre of cultivation, it has been estimated that less than 2-3 percent of total Indian cropping land is sufficient to produce enough biodiesel to replace all petrodiesel currently used in country. Clearly microalgae are superior alternative as a feedstock for large scale biodiesel production (Table.1).

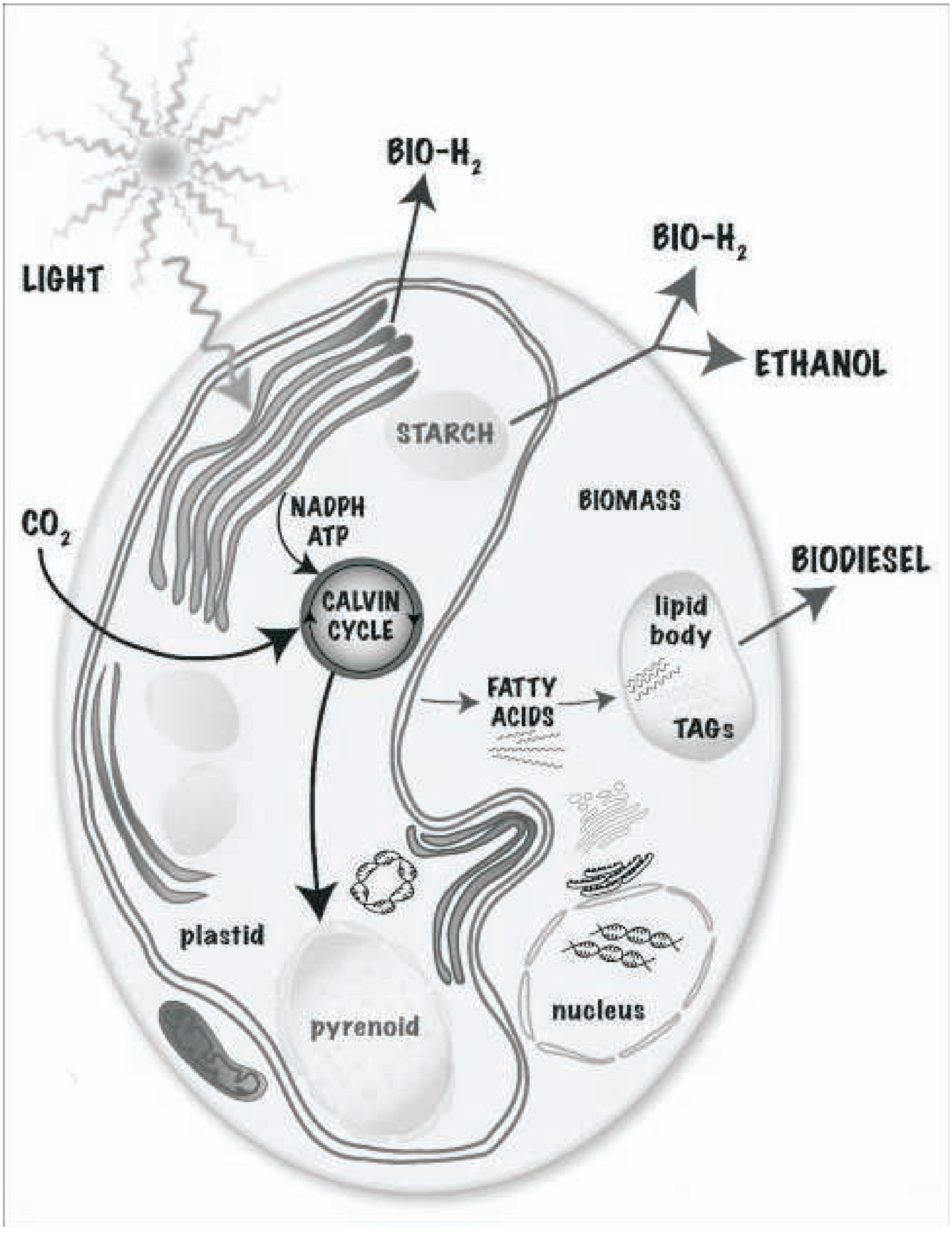
Table 1Comparison of some sources of biodiesel

Crop	Oil yield (L/acre)
Corn	68.13
Soybean	181.68
Sunflower	386.07
Rapeseed	480.69
Canola	495.83
Jatropha	788.33
Oil palm	2403.47
Microalgae	19000-57000

Microalgae appear to be an emerging source of biomass for biodiesel that has the potential to completely displace fossil diesel. Microalgal strains with high oil content are of great interest in search for sustainable feedstock for the production of biodiesel [11, 12]. Algae can have anywhere between 20-80% of oil by weight of dry mass (Table. 2).

Lipid accumulation in algae (Figure 1) typically occurs during period of environmental stress, including nutrient-deficient conditions. Biochemical studies have suggested that acetyl-CoA carboxylase (ACCase), a biotin containing enzyme that catalyzes an early step in fatty acid biosynthesis, may be involved in the control of this lipid accumulation process. Therefore, it may be possible to enhance lipid production rates by increasing the activity of this enzyme via genetic engineering.

Figure 1 Lipid accumulation in algal cell



Production of microalgal biomass

The microalgae can be grown in both open-culture systems such as ponds, lakes and raceways, or in highly controlled closed-culture systems like photobioreactors, similar to those used in commercial fermentation processes. The photosynthetic growth of microalgal biomass require light, carbon dioxide, water, organic salts and temperature of 20-

30 °C. As the production of microalgal biodiesel require large quantities of algal biomass, so to minimize the expense the biomass must be produced using freely available sunlight [13].

Microalgae can be grown on large scale in photobioreactors or raceway ponds [19-22]. A photobioreactor is basically a bioreactor which incorporates some type of light sources. While almost anything that it would be possible to grow algae in could technically be called a photobioreactor, the term is more commonly used to define a closed system. Many different designs of photobioreactors have been developed, but a tubular photobioreactor seems to be most satisfactory for producing algal biomass on the scale needed for biofuel production (Figure 3).A tubular photobioreactor consists of an array of clear transparent tubes that are usually made of plastic or glass. These solar collectors capture the sunlight for photosynthesis. Microalgal broth is circulated from a reservoir such as the feeding vessel/recirculating shown in (Figure 3) to the solar collector and back to the reservoir. A photobioreactor is typically operated as a continuous culture during daylight [13]. In a continuous culture, fresh culture medium is fed at a constant rate and the same quantity of microalgal broth is withdrawn continuously. Feeding ceases during the night; however, the mixing of broth must continue to prevent settling of the biomass [19]. As much as 25% of the biomass produced during daylight might be consumed during the night to sustain the cells until sunrise [23, 24].

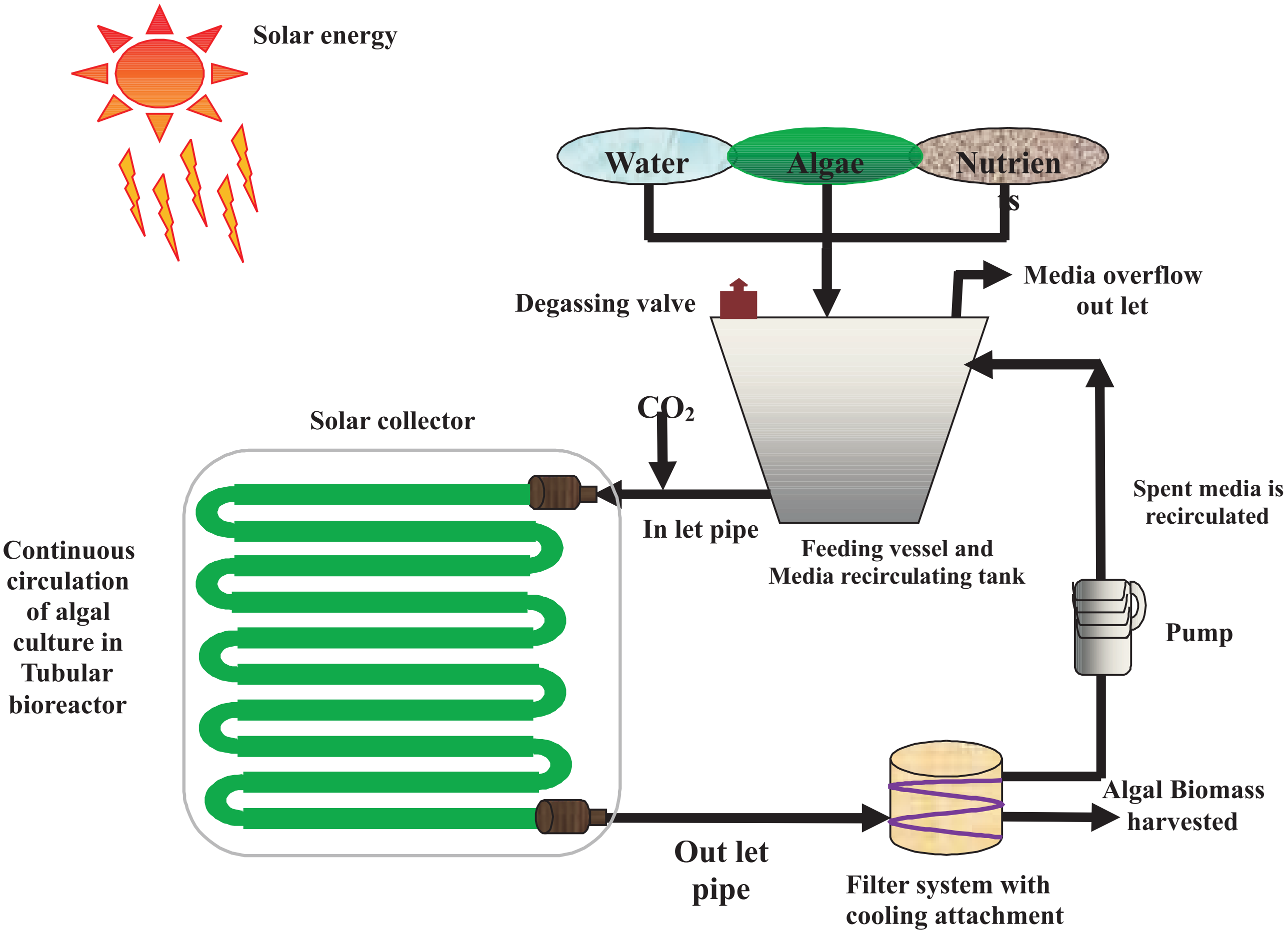


Figure 3 Schematic representation of algal biomass production in tubular photobioreactor

To maximize sunlight capture, the tubes in the solar collector are generally placed horizontally flat on the surface (Figure 3). The ground beneath the solar collector is either painted white or covered with white sheets of plastic [19, 25, 13] to increase reflectance, which will increase the total light received by the tubes. Biomass sedimentation in the tubes is prevented by maintaining a highly turbulent flow. This flow is produced either using a mechanical pump (Figure 3) or a more gentle airlift pump [26-30].

Innovative Approaches for improving algal biomass Yield

Algae cultivation has four basic and equally important requirements: carbon, water, light, and space. By manipulating requirements, it is possible to increase the quantity of oil-rich biomass [13, 31].

Carbon dioxide is the first requirement. In order to maximize algal growth, CO_2 needs to be provided at very high levels, much higher than the naturally available. Rather than becoming an expense, this need for CO_2 creates a unique opportunity to control air pollution and simultaneously reduce the cost of algae culture. The flue gases from industrial processes, and in particular from power plants, are rich in CO_2 that would normally be released directly into the atmosphere and there by contribute to global warming. By diverting the CO_2 fraction of the flue gas to algae cultivation facility, the CO_2 can be diverted back into the energy stream and the rate of algal production can be increased [31, 32].

Water, containing the essential salts and minerals is the second requirement for growth. Fresh water is a valuable resource as for the salts and minerals needed; however, algae cultivation can be coupled to another type of environmental remediation that will enhance productivity while mitigating pollution. High nutrient wastewater from domestic or industrial sources, which may already contain nitrogen and phosphate salts, can be added to the algal growth media directly [33]. This allows for algae production to be improved cheaply, while simultaneously treating wastewater [31].

Abundant light, which is necessary for photosynthesis, is the third requirement. This is often accomplished by situating the facility in a geographic location with abundant, uninterrupted sunshine, this is a favoured approach when cultivating in open ponds. When working with bioreactors, sunlight quality and quantity can be further enhanced through the use of solar collectors, solar concentrators, and fibre optics in a system called photo-bioreactors [13, 31, 34].

Space is the fourth requirement. Other biomass sources require terrestrial cultivation on valuable arable land. This causes a diversion of agricultural produce from the food supply to the energy supply and increases cost of production. Algae cultivation is unique in that it does not require arable land; algae can be cultivated in ponds, in fresh or salt water bodies, waste water streams or in bioreactors. This versatility means that algae production facility can be located anywhere there is cheap, barren or waste land is available [13, 31].

Through the combination of light, water, and carbon fertilization techniques, the production of algae biomass can be enhanced [35]. Another different and complimentary approach to increase productivity of microalgae is via genetic and metabolic engineering. Genetic and metabolic engineering are likely to have the greatest impact on improving the economics of production of microalgal biodiesel [13]. The molecular level engineering can be used potentially to: increase photosynthetic efficiency to enable increased biomass yield on light; enhance biomass growth rate; increase oil content in biomass; improve temperature tolerance to reduce the expense of cooling; and eliminate the light saturation phenomenon so that growth continues to increase in response to increasing light level [13].In addition, there is a need to identify possible biochemical triggers and environmental factors that might favor accumulation of oil. Stability of engineered strains and methods for achieving stable production in industrial microbial processes are known to be important issues [36], but have been barely examined for microalgae.

Extraction of oil form algal biomass for biodiesel Production

Algal biomass is an interesting sustainable feedstock for biodiesel production. It can produce up to 30 times more oil per acre than other oil producing crops [37]. Various methods are available for the extraction of algal oil, such as mechanical extraction using hydraulic or screw, enzymatic extraction, chemical extraction through different organic solvents, Ultrasonic extraction, and supercritical extraction using carbon dioxide above its Standard temperature and pressure.

Enzymatic extraction

In the process of enzymatic extraction water is used as solvent with the cell wall degrading enzymes to facilitate an easy and mild fractionation of oil, proteins and hulls. The oil is found inside plant cells, linked with proteins and a wide range of carbohydrates like starch, cellulose, hemi-cellulose and pectin. The cell content is surrounded by rather thick wall which has to be opened so the protein and oil can be released. Thus, when opened by enzymatic degradation, down-stream processing makes fractionation of the components possible to a degree which cannot be reached when using the conventional technique like mechanical pressing. This is the biggest advantage of enzymatic extraction process over other extraction methods. But the cost of this extraction process is estimated to be much higher than most popularly used solvent based extraction processes [38]. The high cost of extraction serves as a limitation factor for large scale utilization of this process.

Chemical extraction

The Soxhlet method is the most commonly used solvent extraction method, used for the extraction of oil from various plants and algal strains. According to the Soxhlet's procedure, oil and fat from solid material are extracted by repeated washings (percolation) with an organic solvent, usually n-hexane or petroleum ether, under reflux in a special glassware called Soxhlet extractor. The method has got several advantages like large amount of extraction using limited solvent, it is cost effective and become more economical if used at large scale. Despite of these advantages there are certain limitations like, poor extraction of polar lipids, long time required for extraction, hazards of boiling solvents etc. But still this method is the most popular and generally used in all oil extraction laboratories [39].

Ultrasonic extraction

The ultrasonic extraction of algae oil involve intense sonication of liquid which generates sound waves that propagate into the liquid media resulting in alternating high-pressure and low-pressure cycles. During the high pressure cycle ultrasonic waves support the diffusion of solvents, such as hexane into the cell structure. As ultrasound breaks the cell wall mechanically by the cavitations shear forces, it facilitates the transfer of lipids from the cell into the solvent. After the oil dissolved in the cyclohexane the pulp/tissue is filtered out. The solution is distilled to separate the oil from the hexane. Ultrasonication not only improves the extraction of oil from the algae cells but also helps in the conversion into biodiesel [40]. The large scale application of this method is not feasible as it is not cost effective with the amount of oil production.

CO_2 Supercritical Extraction

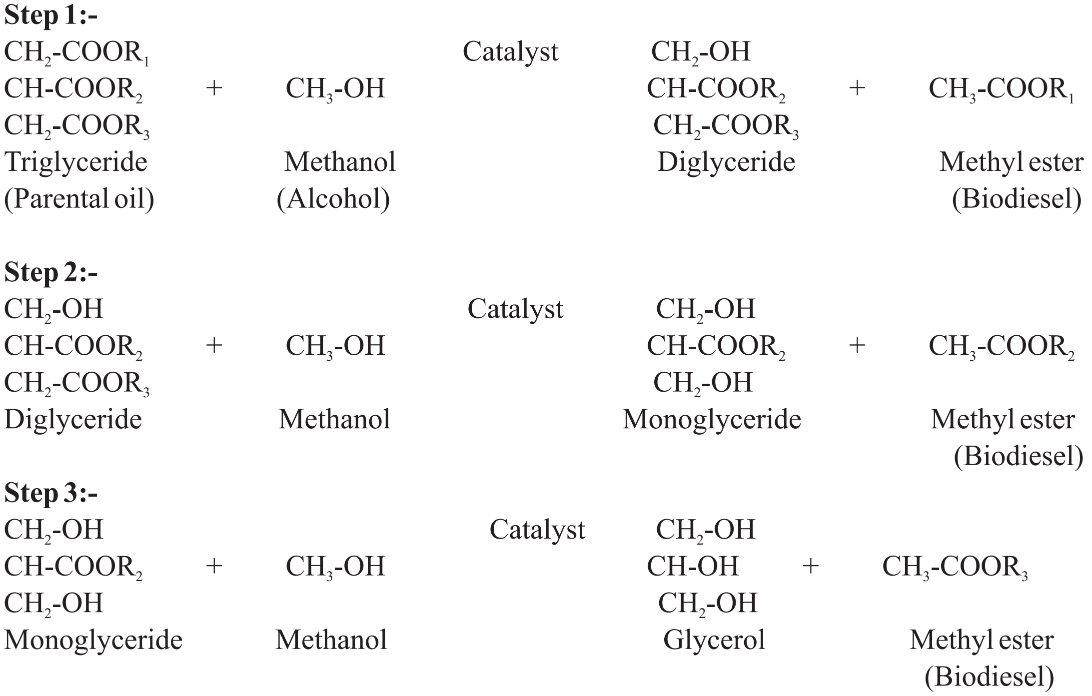
In CO_2 supercritical method, CO_2 is compressed beyond its supercritical point (31°C 74bar) where it obtains substantial solvent power. The supercritical-fluid is brought in contact with algal material in an extraction vessel. Due to its high diffusion rates and gas like low viscosity, CO_2 penetrates into the smallest pores of the starting-material. In a separate vessel CO_2 is de-pressurized and substances of interest are efficiently collected with less solvent residues as compare to other extraction methods [41]. The CO_2 supercritical extraction is the most advanced oil extraction method, besides some disadvantages like elevated pressure requirement and high capital investment for equipment. It has got large number of advantages like, the biomass residues that remains after extraction of oil could be used partly as high-protein animal feed and, possibly, as a source of small amounts of other high-value microalgal products [19, 22, 42]. The algal biomass residue remains after oil extraction can also be used to produce biogas by anaerobic digestion. Which can be further used the primary source of energy for most of the production and processing of the algal biomass. An Additional income could come from the sale of nutrient-rich fertilizer and irrigation water that would be produced during the anaerobic digestion stage [13] (Figure 3). The technology for anaerobic digestion of waste biomass exists and is well developed [43], and the technology for converting biogas to electrical/mechanical power is well established [44]. The carbon dioxide generated from combustion of biogas can be recycled directly for the production of the microalgae biomass.

Conversion of algal oil into biodiesel

The typically used process for commercial production of biodiesel is explained. Any future production of biodiesel from microalgae is expected to use the same process [13].

Transesterification of algae oil

Biodiesel production from microalgae can be done using several well known industrial processes, the most common of which is base catalyzed transesterification with alcohol. The transesterification is the reversible reaction of fat or oil (which is composed of triglyceride) with an alcohol to form fatty acid alkyl ester and glycerol. Stoichio-metrically, the reaction requires a 3:1 molar alcohol to oil ratio, but excess alcohol is (usually methyl alcohol is used) added to drive the equilibrium toward the product side [45]. This large excess of methyl alcohol ensures that the reaction is driven in the direction of methyl esters, i.e. towards biodiesel. Yield of methyl esters exceeds 98% on a weight basis [46]. The reaction occurs stepwise: triglycerides are first converted to diglycerides, then to monoglycerides and finally to glycerol [13]. (Fig. 4) Transesterification can be done in number of ways such as using an alkali catalyst, acid catalyst, enzyme catalyst, heterogeneous catalyst or using alcohol in their supercritical state; however enzyme catalyst are rarely used as they are less effective [47]. The alkali-catalyzed transesterification is about 4000 times faster than the acid catalyzed reaction [46]. Consequently, alkalis such as sodium and potassium hydroxide are commonly used as commercial catalysts at a concentration of about 1% by weight of oil. Alkoxides such as sodium methoxide are even better catalysts than sodium hydroxide and are being increasingly used. Use of lipases offers important advantages [13, 46].



Step 1:-

$$\begin{array}{l} CH_2\text{-}COOR_1 \\ CH\text{-}COOR_2 \\ CH_2\text{-}COOR_3 \end{array} \quad + \quad CH_3\text{-}OH \quad \text{Catalyst} \quad \begin{array}{l} CH_2\text{-}OH \\ CH\text{-}COOR_2 \\ CH_2\text{-}COOR_3 \end{array} \quad + \quad CH_3\text{-}COOR_1$$

Triglyceride (Parental oil) Methanol (Alcohol) Diglyceride Methyl ester (Biodiesel)

Step 2:-

$$\begin{array}{l} CH_2\text{-}OH \\ CH\text{-}COOR_2 \\ CH_2\text{-}COOR_3 \end{array} \quad + \quad CH_3\text{-}OH \quad \text{Catalyst} \quad \begin{array}{l} CH_2\text{-}OH \\ CH\text{-}COOR_2 \\ CH_2\text{-}OH \end{array} \quad + \quad CH_3\text{-}COOR_2$$

Diglyceride Methanol Monoglyceride Methyl ester (Biodiesel)

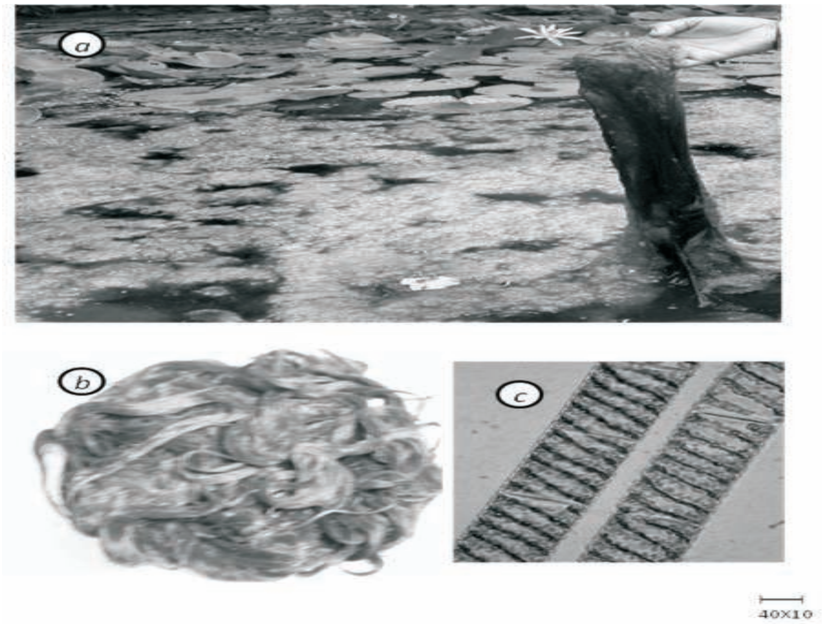
Step 3:-

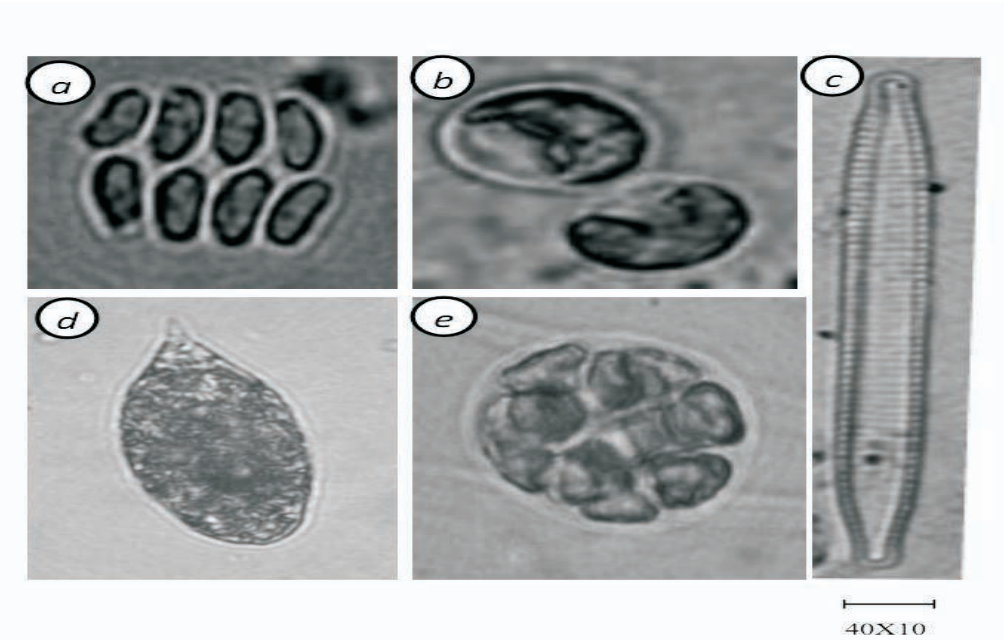
$$\begin{array}{l} CH_2\text{-}OH \\ CH\text{-}COOR_2 \\ CH_2\text{-}OH \end{array} \quad + \quad CH_3\text{-}OH \quad \text{Catalyst} \quad \begin{array}{l} CH_2\text{-}OH \\ CH\text{-}OH \\ CH_2\text{-}OH \end{array} \quad + \quad CH_3\text{-}COOR_3$$

Monoglyceride Methanol Glycerol Methyl ester (Biodiesel)

Figure 4. Transesterification of oil to biodiesel. R1–3 are hydrocarbon groups

Alkali-catalyzed transesterification is carried out at approximately 60°C under atmospheric pressure, as methanol boils off at 65 °C at atmospheric pressure. Under these conditions, reaction takes about 90 min to complete. A higher temperature can be used in combination with higher pressure. Methanol and oil do not mix; hence the reaction mixture contains two liquid phases. Other alcohols can be used, but methanol is the least expensive. To prevent yield loss due to saponification reactions (i.e. soap formation), the oil and alcohol must be dry and the oil should have a minimum of free fatty acids. Biodiesel is recovered by repeated washing with water to remove glycerol and methanol [13]. This process of biodiesel production is found to be most efficient and least corrosive of all the processes as the reaction rate is reasonably high even at a low temperature of 60°C.





Legend to figure 2
(Plate 1)

a. Green algae in natural pond
b. Algal biomass
c. *Spirogyra illinoisense* (Trans.) G.M. Smith

Legend to figure 2
(Plate 2)

a. *Scenedesmus arcuatus* (Lemm.) Lemm.
b. *Chlorella vulgaris* Beijerinck
c. *Nitzschia palea* (Kuetz.) W. Smith
d. *Euglena polymorpha* Dangeard
e. *Botryococcus braunii* Kuetz.

Economics of algal biodiesel production

According to experts algae farming in less than 2-3 percent of India's total land can make the country self-sufficient in liquid fuel. The estimate yield of algae in on acre of wasteland can be 30 times more than Jatropha And not just this, algae farming also provide solution to food verses fuel debate. As algae do not need agriculture land, it can be easily grown in waste/degraded land or sea water, sewage, industrial effluent etc [48]. Some of the Indian experts suggest that the Sundarbans delta archipelago of 100 islands, spread over approx 4,260 sq.km on the Bay of Bengal, can be used for algal cultivation and extraction of biodiesel [49].

The biodiesel from algae can be competitive with petroleum sourced fuel, as these fuels at present are the least expensive transport fuels in India. Whether microalgal biodiesel is competitive or not, is mainly depends on the cost of algal biomass production [13].

Microalgal oils have potential to completely replace petroleum as a source of hydrocarbon feedstock for the petrochemical industry. For this to happen, microalgal oil needs to be produced at a price, which is less than the price of crude oil [13].

It can be conclusively established that, the economics of biodiesel production can be improved by advancing the production technology. As the yield per acre of microalgal oil is already far more than the yield of oil from palm and jatropha plant [50]. While jatropha take 2-3 year for commercial yield, algae start yielding from 2-3 days of plantation, therefore algae oil can be harvested every day. After the conversion of algal oil into biodiesel, the left over part serves as an excellent source of high value protein and can be used to supplement as cattle feed or rich carbon source to be used as soli additive in mulching also as biofertilizer.

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Algal Biodiesel performances

The microalgal biodiesel have many advantages over the traditional diesel fuel, it can reduce net carbon dioxide emission by 78% on a life-cycle basis as compared to traditional diesel fuel [51, 52]. Biodiesel also contain little or no sulfur or aromatic compound; in conventional diesel, the sulfur lead to formation of sulfur oxide and sulfuric acid, while the aromatic compound also increase particulate emission and are considered carcinogens. In addition to reduce CO and particulate emission, the use of biodiesel confers additional advantages, including a higher flashpoint, faster biodegradation and greater lubricity. The higher flashpoint helps in safer handling and storage, whereas biodegradability of biodiesel is particularly advantageous in environmentally sensitive areas [53]. The lubricity of biodiesel is also greater than conventional diesel fuel, and blending biodiesel with low sulfur fuel restores lubricity [54].

However, the biggest advantage of algal biodiesel is that, it's a sustainable source of liquid transportation fuel and derives energy from sun [51]. The combustion of biodiesel in place of conventional diesel fuel can also reduce green house gas emission up to 40% [55].

Algal Biodiesel Opportunities in India

India is a rapidly expanding country in terms of both its population and its economy. According to CIA (Central intelligence agency) Fact book, India's current population is about 1,166,079,217 (Till July 2009). Although India occupies only 2.4% of the world's land area, it supports over 15% of the world's population. Demographics indicate the population will grow because almost 40% of Indians are younger than 15 years of age and are likely to produce offspring [56]. By 2050, United Nations' demographer's project that India will have added another 530 million people for a total of more than 1.5 billion. If India continues on its projected demographic path, it will overtake China by 2045, becoming the world's most populous country.

Economic growth in India, as in many developing and developed countries, is currently correlated with increased energy consumption. The environmental issues often discussed in public policy debates in India arise because of two factors, the sectors responsible for energy use and where economic development is happening.

Although a large proportion of Indians (approximately 70%) live in 550,000 rural villages, urbanization levels have increased consistently since 1971. Many Indians have began congregating in large cities as evidenced by the fact that cities with at least a million people increased from 12 in 1981 to 23 in giant conglomerates Mumbai (12.57 million), Calcutta (10.92 million), Delhi (8.38 million), Chennai (5.36 million) and Bangalore (4.09 million) [56]. In Delhi this has increased the number of registered vehicles to increase from 841,000 in 1985 to over 3.5 million in 2001 [57]. As the consequence of India's rapid economic growth there is severe increase in air and water pollution, deforestation, water shortages, and carbon emissions. The country's carbon emission is also rising due to rapid industrialization, transportation sector growth, and the wide-spread use of coal as a fuel. Due to this large amount of urbanization and industrialization there is sudden rise in utilization of nonrenewable energy sources, which can cause large amount scarcity of these fuels in future. So to prevent such conditions there is an urgent need for alternative sources of energy. According to current research, microalgae seem to be the promising renewable source of energy for India.

The production of biodiesel in India is also attractive for several other reasons. Petroleum diesel fuel has been sold at government subsidized rates in India to keep the transport costs low and increase GDP. Currently, a liter of gasoline normally costs 2.5 times more than a liter of diesel fuel. Taking advantage of this cost differential, Indian car manufacturers have been investing heavily in the production of diesel vehicles. As such, there are a substantial number of vehicles on the road that demand diesel and would not require the relatively expensive retrofits needed to use Compressed Natural Gas (CNG). The final factor making biodiesel production in India attractive is the potential to cultivate cheap feedstocks. India's tropical climate is conducive to grow various species of micro-algae, which serves as natural benefit over other countries for the production of algal biodiesel. The micro-algae produced sufficient quantity of biodiesel to completely replace petroleum [17]. While traditional high oil crops, such palm can produce 2000 to 2500 liter of biodiesel per acre, algae can yield 19,000-57,000 liter per acre [13]. So the adoption of large-scale biodiesel production and consumption can potentially lowers India's dependence on foreign countries for oil and helps improve air quality in major cities like Delhi, Kolkatta, Bengaluru, Chennai, reclaims unusable wastelands, employs unemployed Indians, and keeps the country's economy on track for its planned 8 to 10% annual GDP growth according to 11th five year plan of India.

CONCLUSION

As discussed above, the algal biodiesel production is gaining importance for its ability to replace fossil fuels, its environmental benefits and the fact that it is a renewable source of energy. But the economics of producing microalgal biodiesel need to improve substantially to make it competitive with petrodiesel, which appears to be attainable now. Producing low-cost microalgal biodiesel requires primarily improvements to algal biology through genomics, transcriptomics, proteomics, and metabolomics. Further the recent advancement in photobioreactor engineering can also lower the cost of production. The algal biomass needed for production of large quantities of biodiesel could be grown in these photobioreactors which are cost effective and 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. Achieving the capacity to inexpensively produce biodiesel from microalgae is of strategic significance to an environmentally sustainable society. Extensive efforts are underway to achieve commercial-scale production of microalgal biodiesel which is likely to be possible in near future.

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